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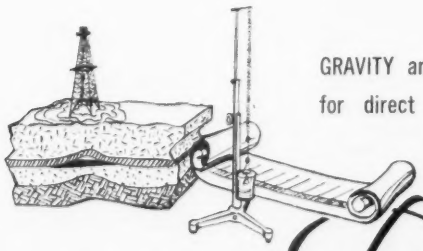

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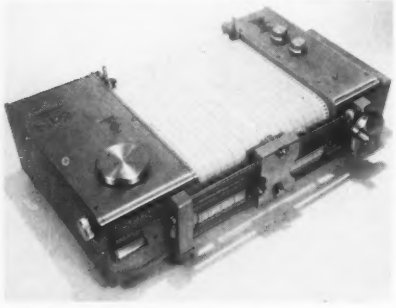

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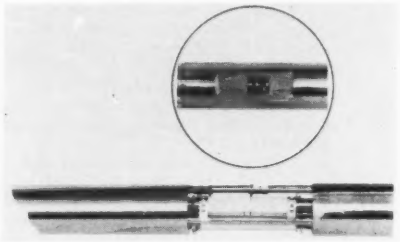

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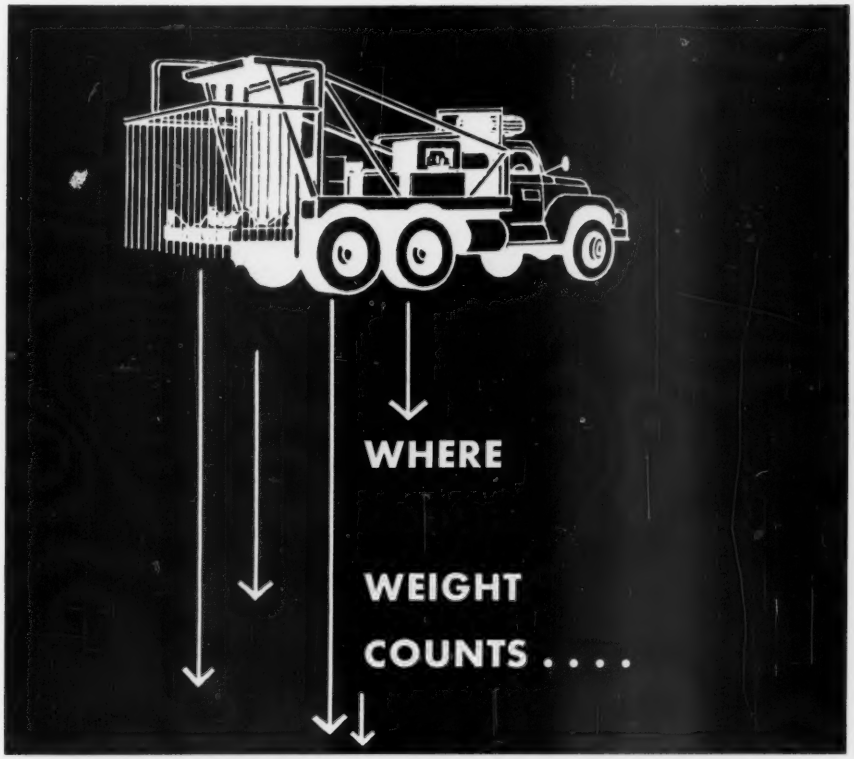

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VOLUME XXVI FEBRUARY, 1961 NUMBER 1

GEOPHYSICS

AN ANALYSIS OF THE OBSERVED TIME DISCREPANCIES BETWEEN CONTINUOUS AND CONVENTIONAL WELL VELOCITY SURVEYS*

P. E. F. GRETENER†

Abstract: Discrepancies between conventionally obtained times and the integrated continuous velocity curves are analyzed (Shell tool only). It is found that these discrepancies may be ascribed to a random scatter and a systematic deviation, the integrated continuous curves being short. Possible causes of these discrepancies are discussed but no final explanation can be offered.

INTRODUCTION

Recently wells have been surveyed for velocity by two different methods. In the conventional method, designated by the letters CON in this paper, a shot is fired at the surface and the time measured to a detector lowered into the hole. In the continuous velocity logging method, designated by the letters CV in this paper, a tool with a sound source and two receivers spaced a few feet apart is lowered into the well and the measured times integrated. In general the two time determinations will not agree and discrepancies up to several tens of milliseconds for deep wells are observed.

The usual procedure at the present time is to survey a well by both methods. When the survey is interpreted the CV data are adjusted to the conventional check-shots. The argument for this procedure generally is, that the CON survey simulates more closely the conditions encountered in seismic shooting.

In this paper a statistical analysis of these discrepancies for 50 wells scattered throughout the Alberta plains (Figure 1) has been performed. Each of these wells has been measured with the Shell CV tool as well as by the conventional method. A concentration of wells is apparent in the Harmattan (23 wells) and Simonette (5 wells) areas where special studies were conducted. All wells are in tectonically undisturbed territory so that the raypath of the conventional surveys should be well defined.

It is the purpose of this study to analyze these discrepancies in detail in order to gain an idea of their cause. Apart from the academic interest, an understanding of these deviations might give more information about the accuracy of well velocity surveys, thus making it possible to abandon the conventional survey.

Some experiments have been performed to investigate the influence and the development of the low velocity zone (invaded zone) surrounding the borehole.

A word of caution should be said about possible conclusions. In the course of this paper it will be obvious, that some of the data are too scanty to be conclusive and that they give mere indications in one way or another. The reader should also be cautioned that all results pertain to data of Western Canada measured with the Shell tool. The writer has no information as to how far these results might possibly be extrapolated.

Instrumentation and Field Procedure

In Figure 2 a conventional survey is schematically outlined. A geophone is lowered to various positions in the hole and, at each level, a shot is fired at the surface, usually about 600 ft from the

* Manuscript received by the Editor June 21, 1960.

† Shell Oil Company of Canada, Limited.

3621 WEST ALABAMA
HOUSTON 27, TEXAS

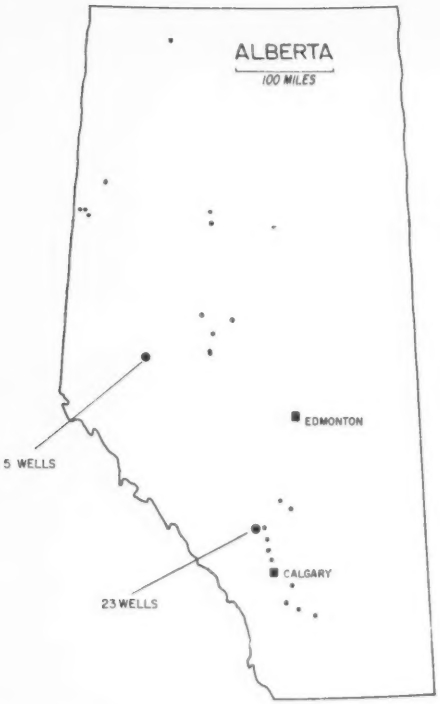

FIG. 1. Locations of wells used in present comparison

wellhead. The measured times are reduced to vertical times by multiplying with cos α. Each position at which a shot is taken is called a check-shot level, while the intervals between them are designated check-shot intervals. Attention is also called to the fact that for the very shallow check-shot levels the raypath is inclined, α becoming 45 degrees or more.

Figure 3 shows the geometry of the Shell CV instrument used in the present study. The transmitter is located at the bottom of the tool, while the first receiver is 4 ft, the second receiver 9 ft away. The distance to the first receiver, called the spacing, determines the penetration of the instrument. The distance between the two receivers, called the span, determines the resolution. The log is taken moving upward at speeds of 4,000 to 6,000 ft per hour. The transmitter emits a signal of about 12,000 cps and the first arrivals at receivers one and two are recorded directly on film (Figure 4). A time marker is put on about every 1,000 ft. The time difference between the arrivals at receivers one and two is read with the help of a template to an accuracy better than ten microseconds (mms), and the log is subsequently integrated manually.

Statistical Analysis of the Discrepancies

The facts about the observed discrepancies are

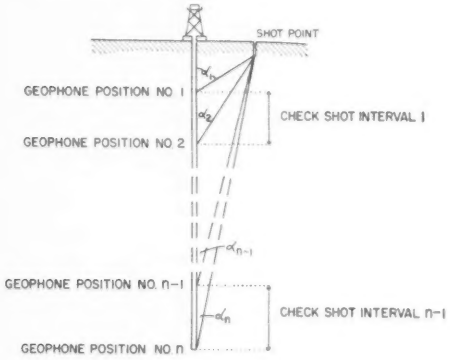

FIG. 2. Schematic sketch of conventional well velocity survey.

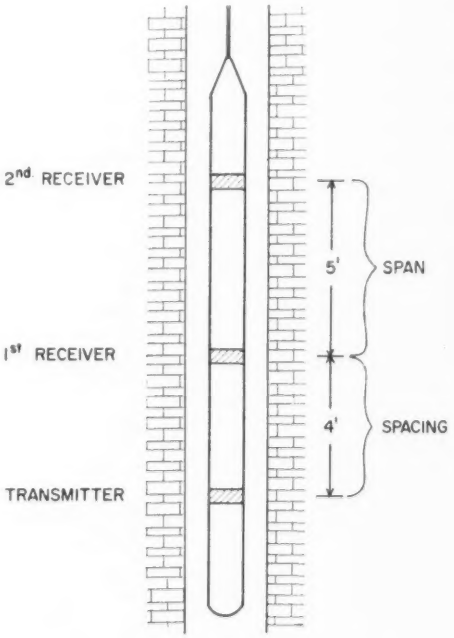

FIG. 3. Schematic sketch of 4×5 CV tool used for present comparison.

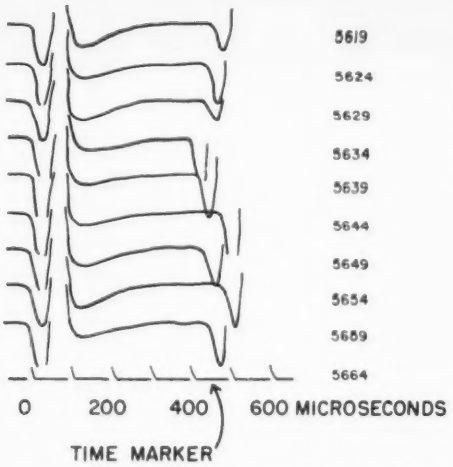

FIG. 4. Basic data as recorded by the Shell CV tool.

presented in Figures 5 to 9. The 50 wells contain a total of 369 check-shot intervals. For each such interval the difference between ΔT_{CON} and ΔT_{CV} was determined, converted to milliseconds per 1,000 ft, and plotted in form of a histogram (Figure 5). An examination of this figure reveals the following facts:

a) There is a normal random discrepancy between the ΔT_{CON} and the ΔT_{CV} indicated by the bell shaped outline of the histogram.[1] The standard deviation from the average is 1.8 ms/1,000 ft.

b) There is a systematic deviation between the ΔT_{CON} and the ΔT_{CV} of 1.7 ms/1,000 ft. This is shown by the fact that the average value (axis of symmetry of the histogram) is shifted to the right of the ordinate by that amount. The CV times are systematically shorter.

Figures 6 and 7 give a further analysis of the

[1] The normal distribution curve for this histogram has been computed using the formula (Dixon and Massey, 1957, p. 49):

$$y = \frac{Ni}{\sigma\sqrt{2\pi}}\, e^{-1/2(x/\sigma-\mu/\sigma)/2}$$

where:

N: number of cases (369)
i: class interval (1ms)
σ: standard deviation
μ: average (1.7 ms/1,000 ft.)

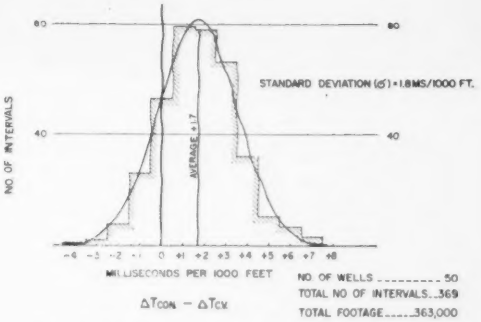
80
40
NO. OF INTERVALS
STANDARD DEVIATION (σ) = 1.8 MS/1000 FT.
AVERAGE = 1.7
-4 -3 -2 -1 0 +1 +2 +3 +4 +5 +6 +7 +8
MILLISECONDS PER 1000 FEET
ΔTCON − ΔTCV
NO. OF WELLS 50
TOTAL NO. OF INTERVALS...369
TOTAL FOOTAGE.....363,000

FIG. 5. Histogram of time discrepancies between CON check-shot and integrated CV intervals converted to milliseconds per 1,000 ft.

same data. In Figure 6 the discrepancies for all check-shot intervals at depths less than 4,000 ft are given, while Figure 7 contains all the discrepancies for check-shot intervals below that depth. For the shallow intervals the systematic deviation amounts to 2.0 ms/1,000 ft while for the deep intervals it is 1.5 ms/1,000 ft. The standard deviations are 1.7 and 1.9 ms/1,000 ft. The significant difference thus lies in the systematic deviation which is about 0.5 ms/1,000 ft larger for the shallow intervals than for the deep ones.

Figure 8 represents a feeble attempt to relate these discrepancies to lithology. Of the total footage shown in Figure 5, over 80 percent is in the Cretaceous, a clastic sequence consisting of shales and sandstones. In Figure 8 only the Paleozoic intervals, i.e. predominantly carbonate rocks have been plotted. The systematic deviation expressed in milliseconds per 1,000 ft is less pronounced; but

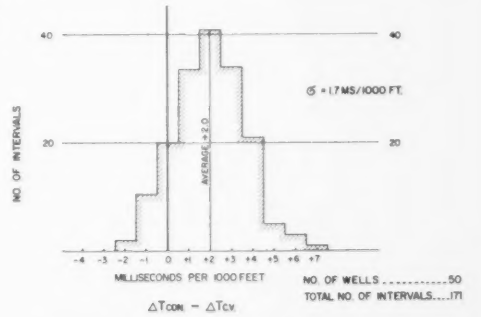
40
20
NO. OF INTERVALS
σ = 1.7 MS/1000 FT.
AVERAGE = 2.0
-4 -3 -2 -1 0 +1 +2 +3 +4 +5 +6 +7
MILLISECONDS PER 1000 FEET
ΔTCON − ΔTCV
NO. OF WELLS 50
TOTAL NO. OF INTERVALS....171

FIG. 6. Histogram of time discrepancies between CON check-shot and integrated CV intervals at depths less than 4,000 ft converted to milliseconds per 1,000 ft.

as will be shown later percentagewise the difference is insignificant.

In Figure 9 the discrepancies between the CON and integrated CV times are plotted against depth. The tie points varying from 600 to 1,500 ft in depth are taken as datum plane. For depth ranges of 1,000 ft average values as well as standard deviations have been computed. An average depth curve is drawn through the average points. This curve is strongly convex at shallow depth, but below 4,000 ft it becomes a straight line. The random scatter (standard deviation) as well as the cumulative systematic deviation increases with depth.

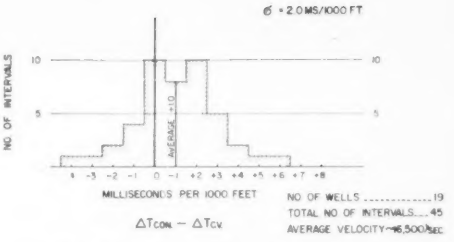
σ = 2.0 MS/1000 FT
NO. OF INTERVALS
AVERAGE +1.0
MILLISECONDS PER 1000 FEET
ΔTcon − ΔTcv
NO. OF WELLS 19
TOTAL NO. OF INTERVALS.... 45
AVERAGE VELOCITY = 6,500 FT/SEC

FIG. 8. Histogram of time discrepancies between CON check-shot and integrated CV intervals for Paleozoic intervals converted to milliseconds per 1,000 ft.

The Systematic Deviation

The following factors may be contributing to a systematic deviation between the two types of surveys:

CON Survey	*CV Survey*
Anisotropy and curved ray-path at shallow depth.	Non-ideal tool geometry.
Delay of signal due to changing electrical properties of setup during the survey.	Wave dispersion in the range of 50 to 12,000 cps.
	Instrumental delay.
	Centering of tool in hole.

Anisotropy.—In a simple case of anisotropy the velocity parallel to the bedding will be higher than at right angles to it. If the beds are undisturbed, this may be written as $V_h > V_z$. The ratio $V_h/V_z = A$ is called the anisotropy factor. In any intermediate direction the velocity will have a value V_θ, whereby $V_h > V_\theta > V_z$. The influence of anisotropy in the shallow layers on a conventional well velocity survey is illustrated in Figure 10. For the very shallow check-shot levels the angle α is large and the ray travels at a velocity V_θ which is about $(V_h + V_z)/2$, while for the deep levels the angle α becomes small and the ray travels through the same shallow layer at a velocity very close to V_z. As a result, an error is committed when correcting the shallow check-shot times to vertical time by a mere multiplication with cos α. The times for the shallow check-shot levels will be short if no allowance is made for anisotropy, while the times for the deep levels will be correct. Figure 11 shows this error as a function of depth for an anisotropy factor of 1.10 and various velocities. The error is zero at the surface,[2] increases to a maximum for α 45 degrees (600 ft in the case of the figure since this is the assumed distance of the shotpoint from the wellhead) and decreases to less than one millisecond below about 4,000 to 5,000 ft. The first check-shot is usually shot at an angle of about 45 degrees and as a result the ΔT_{CON} from the tie point to about 4,000 ft will be too large.

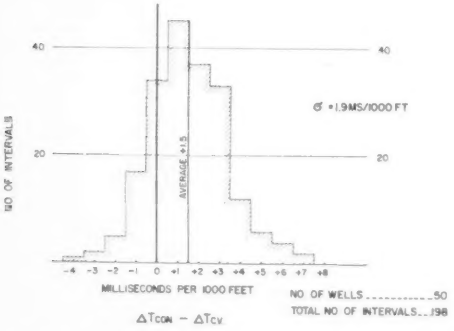

FIG. 7. Histogram of time discrepancies between CON check-shot and integrated CV intervals at depths greater than 4,000 ft converted to milliseconds per 1,000 ft.

It should be noted that a curvature in the ray-path (layering of the medium) will lead to the same type of error. Without having CV data from the grassroots downwards it will in most cases not be possible to determine whether such an error is due to true anisotropy, a curvature of the ray-path, or a combination of both. It is, therefore, preferable to call the observed effect apparent

[2] In practice it is found that values of 50 degrees are not uncommon for the angle α. For higher values of α the curves in Figure 11 are merely the graphical expression of the quoted formula and of no practical significance, since vertical velocities are simply never determined in that manner.

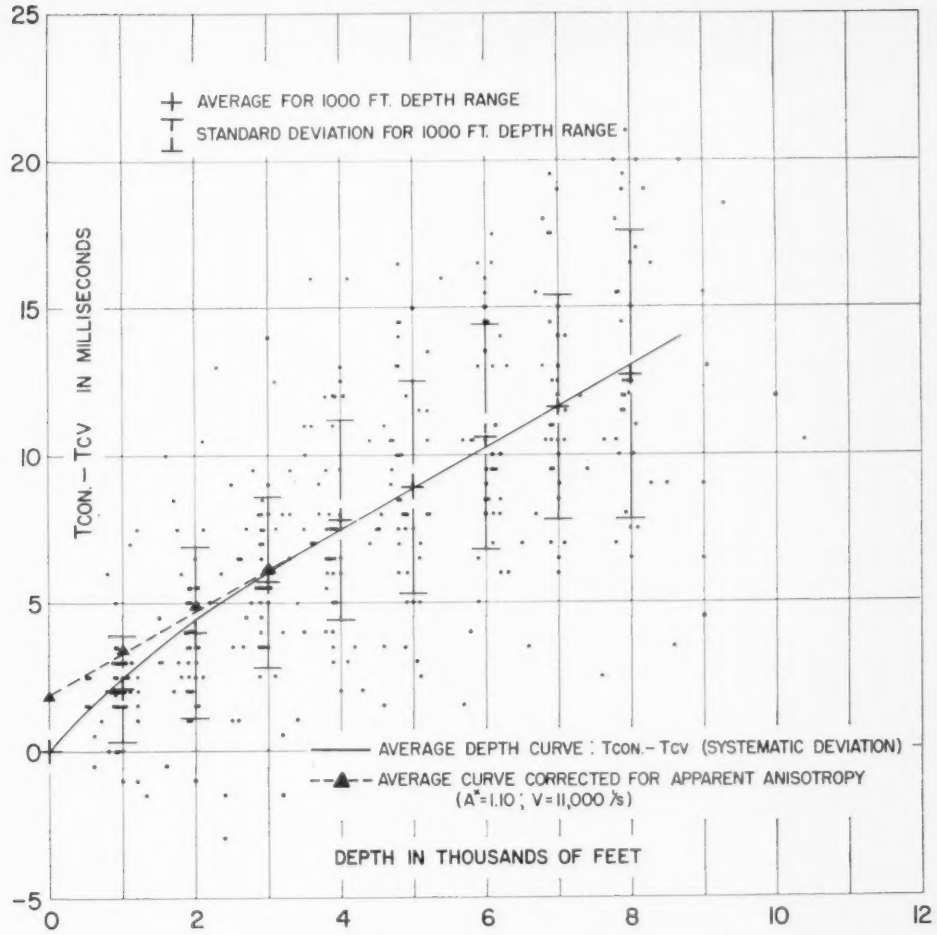

FIG. 9. Differences of CON and integrated CV times at check-shot levels for 50 wells.

anisotropy, which by definition shall include both sources of error. In Figure 9 the average depth curve has been corrected for depths less than 4,000 ft assuming a velocity of 11,000 ft/s and an apparent anisotropy factor (A) of 1.10. Such a correction straightens the shallow, convex part of this curve very satisfactorily. One may, therefore, conclude that the average apparent near surface anisotropy in the Alberta Plains is in the order of 10 percent.

Measurements as well as published information (Cholet and Richard, 1954, Dunoyer de Segonzac and Laherrere 1959, Richards 1960) indicate that anisotropy is indeed a rather common phenomenon. For the purpose of the present investigation it seems thus reasonable to attribute about 0.5 ms/1,000 ft of the observed systematic deviations in the shallow intervals to apparent anisotropy.

Delay of signal due to changing electrical properties.—For the shallow shots the well geophone cable will be on the drum, having a high inductance and a low capacitance, while for the deep check-shots the situation will be reversed. There

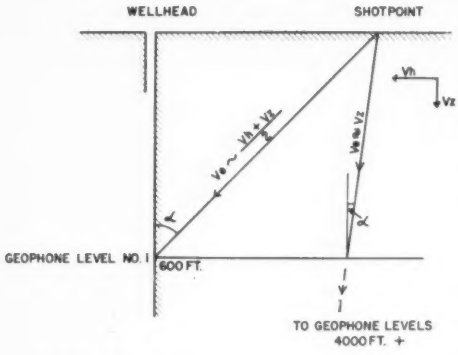

FIG. 10. Effect of anisotropy in shallow layers on conventional well velocity survey.

is no reason to suspect that this might introduce a lag into the CON survey. However, to eliminate this possibility, an experiment was set up whereby a pulse was recorded directly and also after going through the cable and the downhole geophone. No delay was observed. There was an indication, however, that in the case of poor breaks some kind of a later event might be picked rather than the true first arrival.

Non-ideal tool geometry.—Laboratory measurements and surveys in wells (Hicks, 1959, Kokesh and Blizard, 1959, Wyllie, Gregory and Gardner, 1958) indicate that in the invaded zone around a well the velocity is lower than in the virgin formation. The thickness of this low velocity zone depends on various factors, such as porosity, consolidation, and mineralogical composition of the formation penetrated. The CV measurements thus acquire the character of refraction surveys and unless the spacing is sufficiently large (Figure 3), the first arrival will not have travelled through the virgin formation. It is thus desirable to extend the spacing to the maximum possible length which is governed by the strength of the transmitter.

The spacing used in this study is 4 ft which in this area should be sufficient for diameters of the low velocity zone of up to 24 inches. It was suspected that this might not be good enough and an experiment proving this is given in Figure 12. Two wells have been logged with the standard spacing of 4 ft, as well as with a spacing of 9 or 12 ft respectively. The limits of error are somewhat larger than usual, since the runs with the larger spacings were made on an improvised

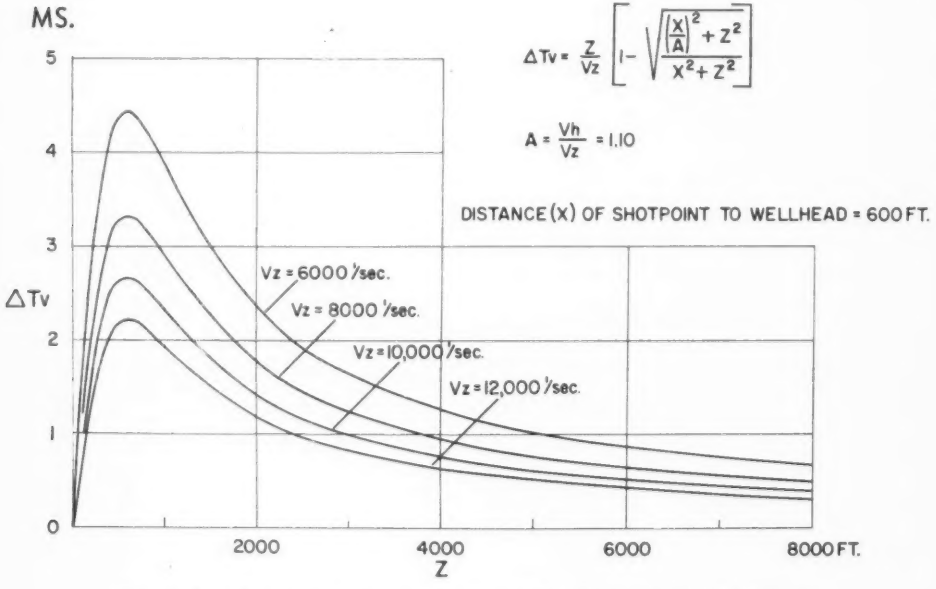

FIG. 11. Error in reduced vertical one way time (Δ Tv) due to omission of anisotropy.

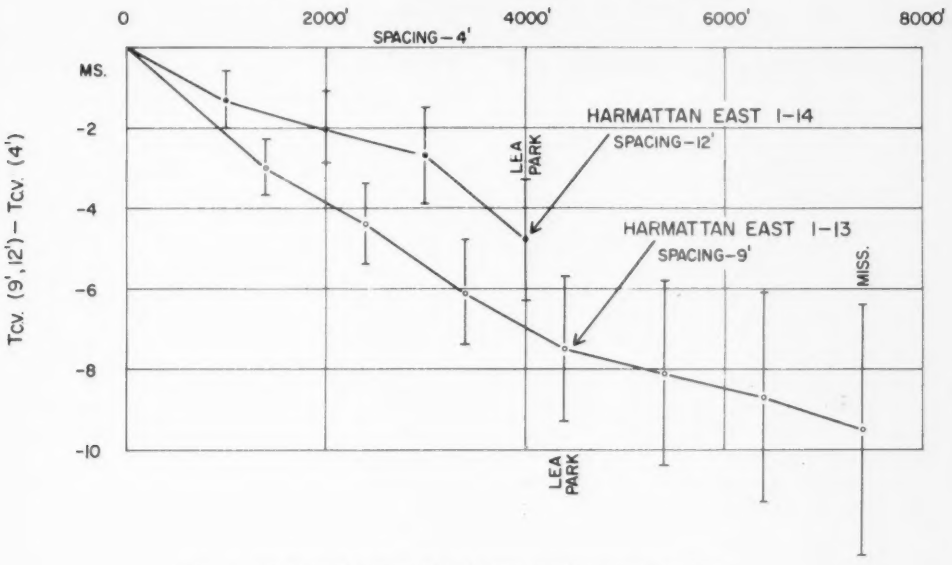

FIG. 12. Variation of integrated CV times as a function of spacing.

basis only and operational difficulties did not permit a further continuation of these experiments. As a result the breaks are not quite up to standard. The section penetrated is one of shales, siltstones and sandstones. The fact that the 9-ft spacing gives even shorter times than the 12-ft spacing seems to indicate that full penetration is achieved at the shorter spacing. The observed discrepancy between the two wells (Figure 12) is most likely an expression of the statistical scatter. Actually the limits of error do touch or overlap each other. The results thus indicate that sufficiently long spacings would give times which are about 1 ms/1,000 ft lower than the ones recorded with the present spacing of 4 ft. The systematic deviations between the two types of survey are thus partially compensated by the non-ideal tool geometry. Using spacings of proper length this deviation would amount to about 2.5 ms/1,000 ft.

Figure 13 shows data which provide an indication of the development of the near borehole low velocity zone with time. In six wells CV measurements have been repeated over the same interval after two months of drilling. While the data are of somewhat less than average quality, indicated by the rather large limits of error, they show quite conclusively that the formation of the low velocity zone is a slow process, taking weeks rather than days. The CV data for the second run read about 0.5 ms/1,000 ft slower than the ones of the first run. Comparing these data with those presented in Figure 12—if such a comparison is permissible—would indicate that half of the time loss for a 4-ft spacing occurs a considerable time after the hole is drilled.

Wave dispersion in the range of 50 to 12,000 cps.—Little information is available regarding wave dispersion. Bruckshaw and Mahanta (1954) have investigated this phenomenon in the range of 40 to 120 cps, for various rock types such as diorite, dolerite, limestone and sandstone. All rocks yield similar curves indicating an increase of the wave velocity with frequency of about 1.5 percent in that frequency range. The velocity-frequency curves are convex indicating that the rate of increase diminishes with higher frequencies.

Birch and Bancroft (1938) have investigated this problem on granite in the range of 140 to 4,500 cps. The flexural, torsional and longitudinal modes were measured. The latter seems to indicate an increase of the velocity of about 0.5 percent in the range of 850 to 4,300 cps which is fairly well within the limit of error. No such in-

crease is apparent from measurements of the other modes. The authors state: "For these frequencies the velocities were independent of frequency to within 1 percent or less." However, from Bruckshaw and Mahanta's data 1 percent is about all one would expect for that frequency range.

At the present one may, therefore, conclude, that there is evidence that the wave velocity does increase with frequency. To what extent this may explain the discrepancies between CON and CV surveys is uncertain. The data of Bruckshaw and Mahanta are of little value insofar as the frequencies observed in CON surveys are close to the upper limit measured by these authors. The data of Birch and Bancroft seem to be of insufficient accuracy in order to be conclusive for this purpose. It thus becomes essential to carry out experiments in the frequency range of 100 to 10,000 cps in order to find out how much wave dispersion might contribute to the observed systematic deviations.

CV instrumental delay.—The arrivals at both receivers are fed through identical channels. Under these circumstances a time loss seems inconceivable. The timing circuit has been checked at various times against standard time signals. It is, therefore, unlikely that the observed systematic deviation is instrumental.

Centering of the CV tool.—The tool is equipped with rubber centralizers of about 5 inches diameter. With the high logging speeds, the flow of the mud around the tool will also tend to keep the tool centralized. A systematic deviation due to a constant list of the tool in the hole, therefore, seems improbable.

In conclusion one may thus say that the observed deviation is real. It is quite likely that wave dispersion in the range of 50 to 12,000 cps may be a major contributing factor. However, further experimental confirmation is needed on this problem.

The Random Discrepancy

In Figure 9 it is plain that the random scatter increases with depth. This is also brought out by

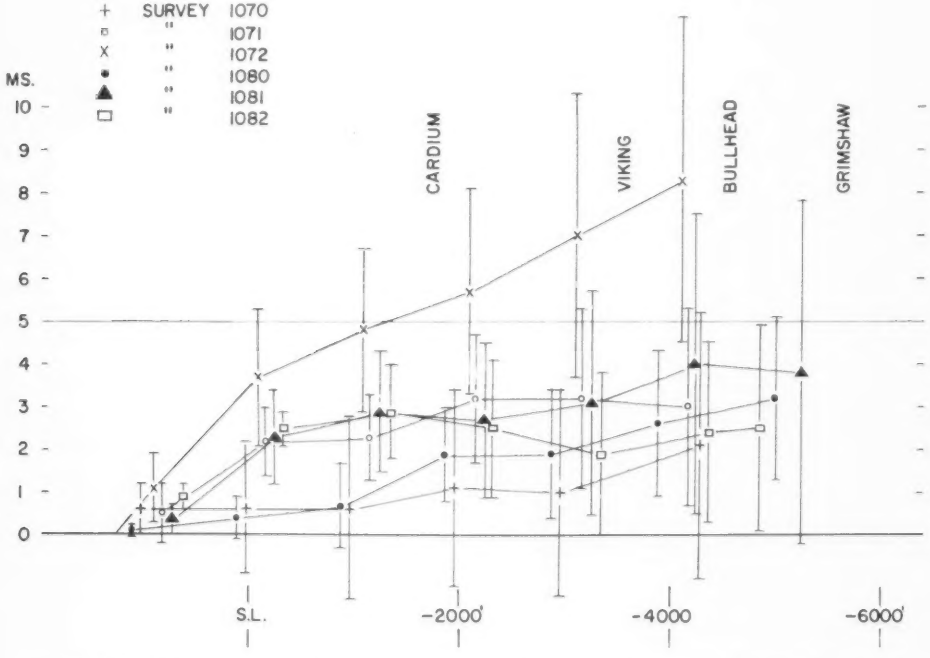

FIG. 13. Variation of integrated CV times for two runs two months apart for six wells in the Simonette area.

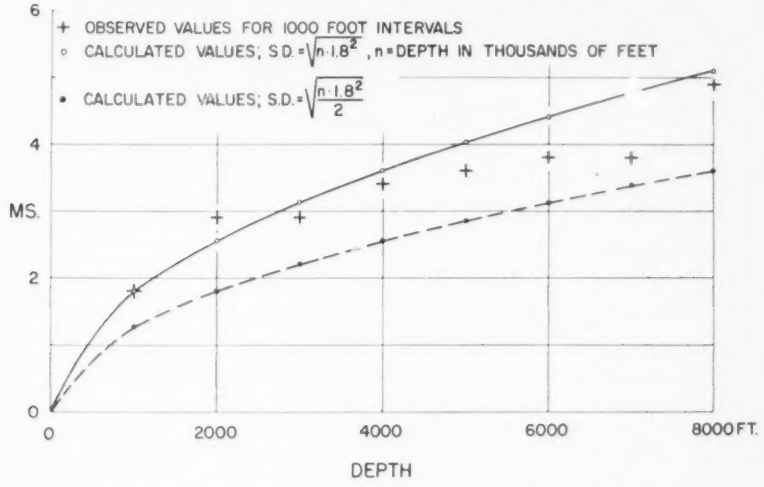

FIG. 14. Increase of the standard deviation (random discrepancy) with depth.

the fact that the standard deviation for consecutive depth ranges becomes larger. In Figure 14 the cumulative standard deviations for 1,000-ft depth ranges have been plotted against depth. It increases from 1.8 ms for the range of 500 to 1,500 ft to 4.9 ms for the range of 7,500 to 8,500 ft. Figure 5 shows the standard deviation for a 1,000-ft interval to be 1.8 ms. It is, therefore, possible to compute a theoretical depth curve of the standard deviation using the formula:

$$\sigma(n) = \sqrt{1.8^2 \cdot n}$$

where

σ = Standard Deviation,
n = depth in thousands of ft.

Figure 14 shows the computed curve to be a fair fit of the observed increase of the random scatter with depth. The randomness of the observed values may be attributed to the following sources:

1. Inaccuracy of the CON survey.
2. Inaccuracy of the CV integration.[3]
3. Randomness of penetration, due to varying thickness of the low velocity zone.
4. At shallow depth, variable apparent anisotropy.
5. Randomness in the wave dispersion, due to variations in frequency observed in the CON survey.

[3] Experiments making several independent integrations show this to be:

$$\sigma(5{,}000') = 1.1 \text{ ms.}$$

No attempt is made here to compute the contributions of these various factors quantitatively since the role of some of them is insufficiently understood.

When plotting the depth-scatter diagram as shown in Figure 9 for local areas such as Harmattan or Simonette only, it seems that for shallow depths the scatter is smaller while for great depths it is about the same as for the whole region. The scatter between CV and CON data for great depths thus seems to be about the same for local areas of a few square miles as for regions of the size of Alberta.

Empirical Corrections of the CVL Measurements

The analysis in the foregoing paragraphs permits one to make an empirical correction of the CV surveys. This may be done in two ways:

a) In depth, by adding 1.7 ms/1,000 ft; this being the average systematic deviation as determined from Figure 5.
b) In time, by multiplying the integrated CV times with a factor 1.02; 2 percent being the average deviation in percent (see below).

Figure 15 presents a histogram of the CON and CV time differences at all check-shot levels after an additive correction of 1.7 ms/1,000 ft has been applied to the CV data. The standard deviation is 3.6 ms and the maximum observed error 11 ms. It is felt that this is too large to permit an abandonment of the check-shots at the present time.

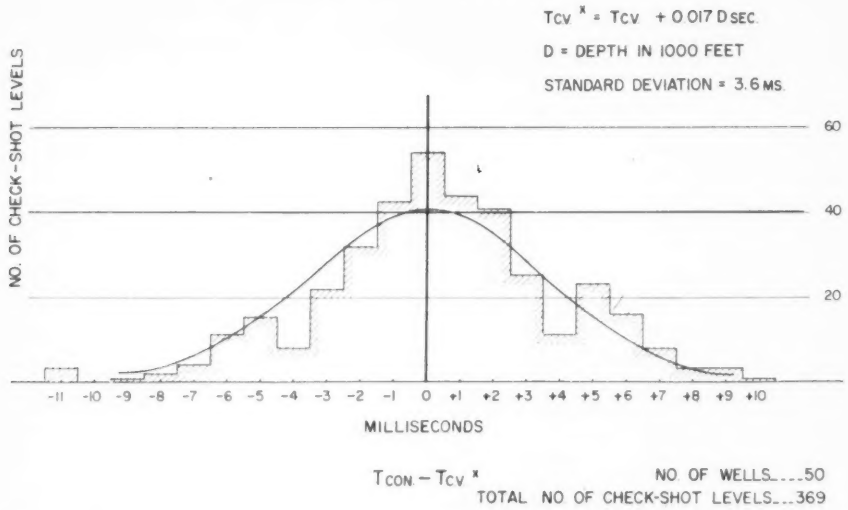
Tcv x = Tcv + 0.017 D sec.
D = DEPTH IN 1000 FEET
STANDARD DEVIATION = 3.6 ms.
NO. OF CHECK-SHOT LEVELS
60
40
20
-11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5 +6 +7 +8 +9 +10
MILLISECONDS
Tcon − Tcv x
NO. OF WELLS....50
TOTAL NO. OF CHECK-SHOT LEVELS...369

FIG. 15. Histogram of the time discrepancies between CON and corrected CV times at check-shot levels.

The histogram for the mode (b) correction is for all practical purposes identical with one shown in Figure 15.

Under (b) in the above paragraph the systematic deviation has been expressed in percentage form. It may be interesting to analyze this type of presentation somewhat further. For this purpose the data have been studied according to average interval velocities.

Average Velocity	Total Time	System. Deviation	Correction	Deviation
ft/s	ms/1,000 ft	ms/ 1,000 ft	ms/1,000 ft	percent
10,900	91.7	2.1	−0.5[4]	1.75[4]
14,200	70.4	1.3	—	1.85
16,500	60.6	1.0	—	1.65

The above table indicates that the observed systematic deviation is independent of velocity. In an earlier paragraph it was found that due to insufficient tool geometry the measured CV times are actually too long by about 1 ms/1,000 ft. Allowing for this the percentage difference increases to about 3 percent.

Determination of the Desirable Check Shot-Interval

The length of the check-shot interval obviously depends on the error which may be tolerated. It will always be possible to compute the time to any intermediate point from a check-shot above as well as one below. The resulting time will thus be the mean value of two determinations. According to statistical theory the standard deviation of such a point will be that for half the check-shot interval divided by $\sqrt{2}$ (Dixon and Massey, 1957, p. 39). These values are given in Figure 14 by the dashed curve, whereby the depth values on the abscissa represent half the check-shot interval. For 1,000 ft (half the check-shot interval) the dashed curve indicates a standard deviation of about 1 ms (max. possible error about 3 ms). Thus, if the check-shots are spaced 2,000 ft apart the intermediate points can be determined with an accuracy of about 1 ms.

The above considerations only indicate how well a computed intermediate point would agree with a hypothetical check-shot at that particular level. No reference is made as to the absolute accuracy of this point. It also should be noted that in order to obtain such an agreement the CV data have to be corrected for the systematic deviation either by mode (a) or (b) as given in the previous paragraph.

[4] Correction for apparent anisotropy from Figure 9, since all intervals are above 4,000 ft.

CONCLUSIONS

(Valid for measurements with the Shell CV tool in Western Canada.)

1. There is a systematic deviation between the CON and CV measurements to the effect that the latter give times which are consistently shorter (1.5 ms/1,000 ft or 2 percent).
2. Present data indicate this deviation to be independent of velocity and lithology.
3. A spacing of 4 ft is insufficient; larger spacings results in CV times which are about 1 ms/1,000 ft shorter. Allowing for this the systematic deviation increases to about 2.5 ms/1,000 ft or 3 percent.
4. Anisotropy and curvature of the raypath are contributing to the systematic deviation in the shallow intervals. Measurements (not given here) and published figures show that values of A up to 10 percent are quite common.
5. The formation of a low velocity zone around a borehole is a slow process, taking weeks rather than days.
6. Check-shots cannot be abandoned at the present time. They may, however, be spaced 2,000 feet apart without a serious loss of accuracy, provided the CV data are empirically corrected for the systematic deviation.

ACKNOWLEDGMENTS

The writer would lik to thank the Shell Oil Company of Canada, Limited for permission to publish this paper. Helpful suggestions and criticisms were received from various colleagues, in particular Messrs. A. Junger, H. C. Maliphant and F. Ustina. The field experiments were carried out by Mr. E. Kung.

EDITOR'S NOTE

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It has been reprinted in GEOPHYSICS because of the desirability of larger circulation amongst Geophysicists.

REFERENCES

Birch, F., and Bancroft, D., 1938, Elasticity and internal friction in a long column of granite: Bull. Seis. Soc. Am., v. 23.

Bruckshaw, J. M., and Mahanta, P. C., 1954, The variation of the elastic constants of rocks with frequency: Petroleum, v. 17, no. 1.

Cholet, J., and Richard, H., 1954, A test on elastic anisotropy measurements at Berriane (North Sahara): Geophysical Prospecting, v. 2, no. 3.

Dixon, W. J., and Massey, F. J., 1957, Introduction to statistical analysis: McGraw-Hill, New York.

Dunoyer de Segonzac, P., and Laherrere, J., 1959, Application of the continuous velocity log to anisotropy measurements in northern Sahara; results and consequences: Geophysical Prospecting, v. 7, no. 2.

Hicks, W. G., 1959, Lateral velocity variations near boreholes: Geophysics, v. 24, no. 3.

Kokesh, F. P., and Blizard, R. B., 1959, Geometrical factors in sonic logging: Geophysics, v. 24, no. 1.

Richards, T. C., 1960, Wide angle reflections and their application to finding limestone structures in the foothills of Western Canada: Geophysics, v. 25, no. 2.

Wyllie, M. R. J., Gregory, A. R., and Gardner, G. H. F., 1958, An experimental investigation of factors affecting elastic wave velocities in porous media: Geophysics, v. 23, no. 3.

GEOPHYSICS, VOL. XXVI, NO. 1 (FEBRUARY, 1961), PP. 12-26, 11 FIGS.

GEOPHYSICAL STUDY OF SUBSURFACE STRUCTURE IN SOUTHERN OWENS VALLEY, CALIFORNIA*

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Abstract: Gravity and seismic measurements in southern Owens Valley, California, have outlined a deep subsurface trough, bounded throughout the greater part of its length by steep faults. Depths to the bedrock floor along the central part of the valley range from 3,000 to 9,000 ft below the surface. The subsurface trough is divided into two parts, a narrow channel-like depression near Lone Pine bounded by northwest-trending faults, and a broad basin at Owens Lake bounded by a more complex series of border faults. The bedrock ridge that crops out to form Alabama Hills is shown to extend from Independence to the north edge of Owens Lake, nearly twice its visible extent. The main direction of faults that have formed the valley is northwest; subsidiary faults trend north, northeast, and east. A fairly sharp velocity boundary within the Cenozoic valley deposits suggests a change in the rate and character of deposition which was probably the result of renewed uplift in the nearby mountains.

INTRODUCTION

Owens Valley in east-central California is a long, narrow, northwest-trending depression that separates the Sierra Nevada on the west from the Basin and Range Province on the east. The area described in this paper comprises approximately the southern half of the valley, extending southward from Independence to Haiwee Reservoir, a distance of about 45 miles (Figure 1). The valley floor, which lies at an altitude of about 4,000 ft above sea level, ranges in width from about 5 miles near Lone Pine to more than 10 miles in Owens Lake. The surrounding mountain ranges rise from 3,000 to more than 10,000 ft above the valley floor.

In earlier geologic investigations of the eastern front of the Sierra Nevada, Owens Valley has been described as a downdropped fault-block or graben structure. This conclusion is based for the most part on the physiographic evidence of steep escarpments that form the valley walls. The present study was undertaken to determine the probable depth and attitude of the buried bedrock surface using geophysical methods, and to relate these results to the structure of the valley. The investigation is a continuation of earlier studies in northern Owens Valley and Long Valley (Pakiser and Kane, 1956); more recently related work has been done in Mono Basin (Pakiser, Press, and Kane, 1960). Gravity measurements were made during March and April 1956, and July 1957. The seismic field work was done during June 1958, in cooperation with the Seismological Laboratory of California Institute of Technology.

Earlier, Gutenberg and others (1932) made seismic experiments in the vicinity of Alabama Hills. More recently, Oliver (1956) made gravity measurements across Owens Valley near Lone Pine. The measurements outlined a large negative anomaly which indicates the great thickness of Cenozoic deposits in the valley east of Lone Pine.

Most of the geologic information is taken from the first comprehensive report on the area by Knopf (1918). Later papers by Hopper (1947) and Mayo (1941, 1947) have also been used. The geology of the region as shown in Figure 2 is generalized from the compilation by Bateman and Merriam (1954).

GRAVITY SURVEY

The clastic rocks that underlie most of the val-

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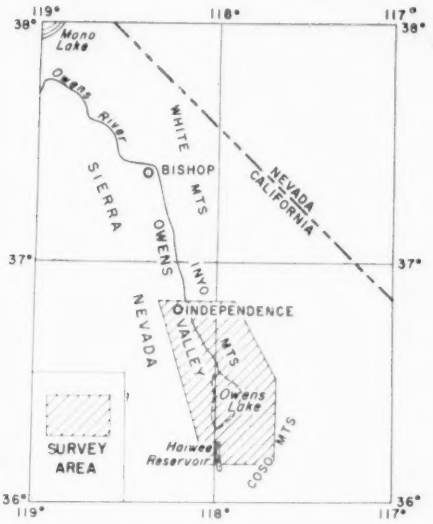

FIG. 1. Index map.

ley interior have been eroded from the bedrock of the surrounding mountains and, because of their high porosity, are considerably less dense than the parent rock. Thick sequences of such deposits fill depressions in the more dense bedrock causing large negative gravity anomalies. The interpretation of the anomalies depends for the most part on the assumption of a suitable density contrast between the clastic deposits and the bedrock. A consideration of probable densities, combined with the results of surveys in areas similar to Owens Valley (Mabey, 1956; Bean, R. J., written communication; Pakiser, Press, and Kane, 1960), indicates that the density contrast can be predicted with an accuracy that will give reliable results.

GRAVITY MEASUREMENTS

More than 450 gravity stations were established over an area of about 700 square miles, using a Worden gravity meter with a scale factor of about 0.5 mgal per dial division. The measurements were corrected for change in base reading, latitude, elevation, and terrain effects. Terrain corrections were made using the Hayford-Bowie system as modified by Swick (1942, p. 67–68). The corrections extend through zone "0," which includes all terrain within about 100 miles of the station. A density of 2.67 g per cm^3 was used for the elevation and terrain corrections. The greatest source of inaccuracy is in the terrain corrections which range from 5 mgals in the valley interior to 25 mgals along the mountain walls. These corrections are estimated to be accurate within ± 10 percent.

ROCK DENSITIES

The rocks of the area, insofar as they affect the gravity field, can be divided into three groups. Granitoid rocks of Cretaceous(?) age form the main mass of the Sierra Nevada and Coso Mountains, and parts of the Inyo Mountains. The densities of these rocks range from 2.55 to 2.75 g per cm^3 with an average of about 2.65 g per cm.^{3} Pre-Cretaceous sedimentary rocks comprise the larger part of the Inyo Mountains and are mainly highly indurated shales, sandstones, limestones, and dolomites. The range in densities for these rocks is greater than for the granitoid rocks, but the average is about 2.75 g per cm.^{3} Densities of poorly consolidated clastic rocks cover a wide range and there are inherent difficulties in devising a suitable sampling technique. However, when such factors as sorting, water content, and probable compaction are considered, a density range of 2.0 to 2.4 g per cm^3 seems plausible. Thompson and Sandberg (1958, p. 1271, 1273) have estimated an average density of 2.2 g per cm^3 for intermontane basin deposits in the Virginia City-Mount Rose area, about 200 miles to the northwest.

Locally, the Cenozoic volcanic rocks and pre-Cretaceous metavolcanic rocks produce changes in the gravity field, but most of these changes are too small to be pertinent to the present discussion.

The average density contrast between the clastic deposits and the enclosing bedrock is estimated as 0.5 g per cm^3. Density contrasts in other intermontane basins of the Great Basin have been calculated directly by comparing seismic and drill hole data with gravity measurements (R. J. Bean, written communication; Mabey, 1956, p. 849). The results range from 0.4 to 0.6 g per cm^3, a range which includes the estimated density contrast for southern Owens Valley.

POROSITY AND DENSITY CONTRAST

In arid and semi-arid regions the contrast in density between clastic deposits and the parent

rock from which they are eroded is largely a matter of porosity because the products of erosion differ only slightly in composition from the parent rock. Maximum porosity is present in clastic deposits having equal grain size, and ranges from about 26 percent to about 48 percent depending on the efficiency of the packing arrangement (Lahee, 1941, p. 62). If the parent rock has a density of 2.7 g per cm^3 and the grain size of the derived sediments is nearly constant, the maximum theoretical density contrast due to porosity ranges from 0.7 to 1.3 g per cm^3 for dry sediments and from 0.4 to 0.8 g per cm^3 for saturated sediments. If the average packing efficiency is assumed to be midway between the most efficient (26 percent) and the least efficient (48 percent), the density contrast over saturated, equi-grained sediments is about 0.6 g per cm^3. When the grain size is assumed to vary, the porosity and therefore the density contrast become less.

In intermontane valleys, the range in grain size is smallest in the central basin deposits, becomes larger in the transition zone between these deposits and the alluvial fans, and finally becomes exceedingly large in the heterogeneous materials that make up the fans. From considerations of porosity it is estimated that the density contrast is about 0.6 g per cm^3 over the central basin deposits, decreases to 0.4 or 0.3 g per cm^3 in the transition zone between these deposits and the alluvial fans (including the lower part of the fans), and then decreases further, possibly reaching 0.1 g per cm^3 over the higher and more heterogeneous part of the fans.

Because of compaction, the porosity of the clastic deposits also decreases with depth, with the greatest change taking place in the fine-grained deposits. The result is a net decrease in density contrast with depth assuming that the bedrock density remains constant.

On the basis of porosity, it can be concluded from the surface distribution of the deposits that the central basin deposits probably predominate and that the average density contrast is about 0.5 g per cm^3.

GRAVITY ANOMALY MAP

Figure 2 is a gravity contour map of southern Owens Valley. The datum is referred to the U. S. Coast and Geodetic Survey Pendulum Station No. 1030 (Duerksen, 1949) about 2 miles south of Independence. One thousand milligals have been added to the complete Bouguer gravity values so that all the units are positive.

The regional gravity, as shown by measurements in the mountain areas, decreases to the west at about 2 mgals per mile. The decrease is part of the large negative anomaly that is present over the Sierra Nevada (Oliver, 1956). There is little evident change in the regional component along the Sierra Nevada front except in the area southwest of Olancha. Knopf (1918, p. 70–71) describes the presence in this area of plutonic complexes having mafic rocks as a major constituent. The mafic rocks are probably the cause of the increase in the gravity field to the south.

On the eastern side of the valley, a positive gravity anomaly is outlined over the sedimentary and volcanic rocks of the Inyo Mountains. The coincidence of the gravity high and the rock types suggests that the sedimentary and volcanic rocks have a higher density than the granitoid rocks to the north and south. A series of andesitic dikes are also present in this area and strike northwest along the trend of the anomaly. The coincidence of the dikes and the gravity high suggest, as an alternate possibility, the presence of a mafic intrusive at depth. The Cerro Gordo orebodies are also located near the center of the gravity high.

Between Alabama Hills and the Inyo Mountains, the gravity field indicates the presence of a deep, narrow, bedrock trough bounded along its east and west edges by steep faults. The bedrock ridge that crops out to form Alabama Hills is shown to extend from near the southern limit of outcrop to the vicinity of Independence, approximately twice its visible extent. The block is bounded along its east edge (the west edge of the adjoining basin) by a steep fault, and seems to have well-defined north and south ends. The nature of the west edge of this block is indeterminate from gravity, but from geologic evidence it appears to be in fault contact with the main mass of the Sierra Nevada.

In the Owens Lake area, the gravity field indicates a broad, deep basin with a northerly trend. The boundary faults form a more complex pattern than those to the north, and the northerly trend diverges from the normal northwest direc-

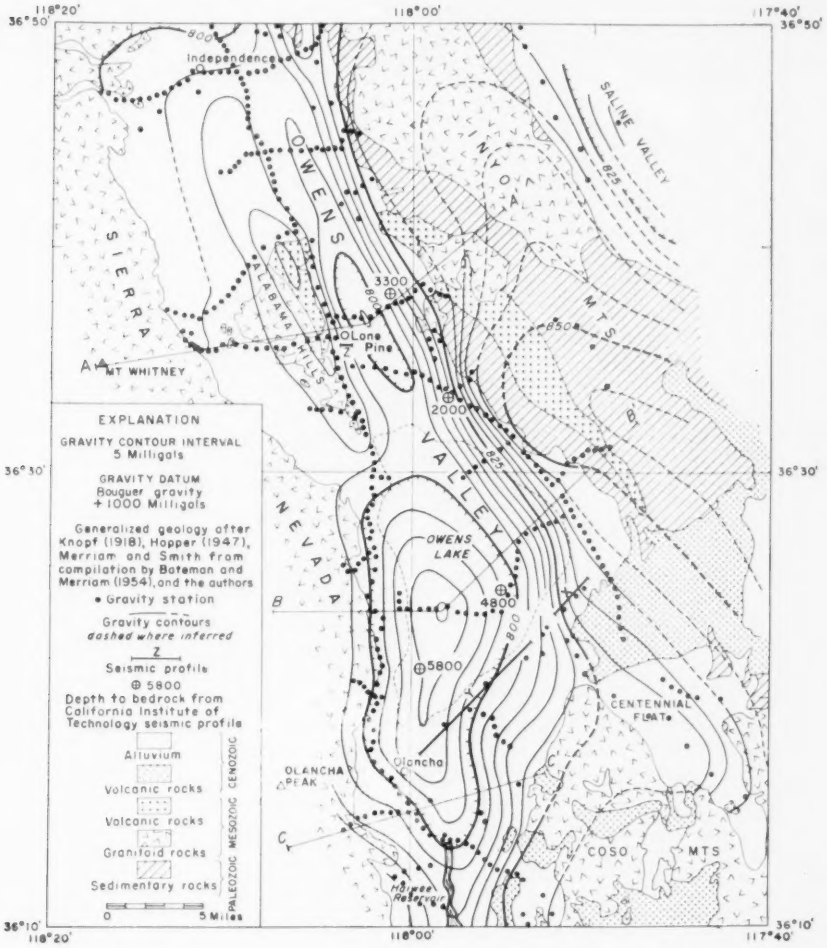

FIG. 2. Geologic and gravity anomaly map of southern Owens Valley.

tion of Owens Valley. In the northeast part of the basin the steep gravity gradient indicates that the subsurface valley wall strikes across an alluviated embayment in the Inyo Mountains at a considerable distance from the alluvium-bedrock surface contact. In the part of the basin south of profile B-B′ (Figure 2) steep gravity gradients and presumably steep subsurface bedrock slopes trend in several different directions. However, the sum effect of the trends is to establish the northerly direction of the basin.

ANALYSIS OF THE GRAVITY PROFILES

Gravity profiles A-A′, B-B′, and C-C′ (Figures 4, 5, and 6) were selected normal to the main trends of the gravity field and near traverses along which the field measurements were made. For profile A-A′ the density contrast was assumed to be 0.4 g per cm^3 instead of 0.5 g per cm^3 to account for the greater proportion of coarse clastic rocks that is probably present in the narrower part of the valley.

Although the density contrast is not a simple

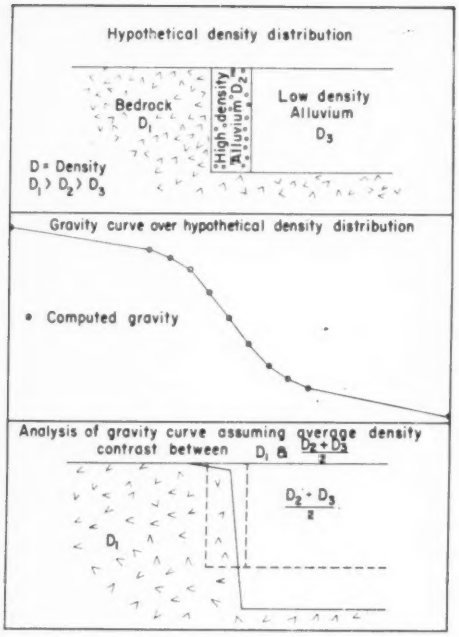

FIG. 3. Error introduced by assuming simple density contrast between alluvium and bedrock where alluvium of two densities is present.

one, an average value was used because the changes in contrast are not known with sufficient precision. Figure 3 shows the effect of assuming an average density contrast for a structure which actually has intermediate-density material interposed between low-density and high-density material, a condition analogous to high-density bedrock, intermediate-density alluvial fans, and low-density central basin deposits. The diagram shows that (1) the bedrock-alluvium contact is displaced towards the bedrock, (2) the upper right-hand corner of the bedrock is displaced beneath the surface, (3) the thickness of the alluvium is too great, (4) the bedrock-alluvium interface is displaced towards the alluvium, and (5) the inclination of the bedrock-alluvium interface is decreased. For the case of a decrease in density contrast with depth, the use of an average density contrast results in depths that are too great, but only in slight changes in the position and inclination of the bedrock-alluvium contacts. Because of these effects, the subsurface configurations shown in Figures 4, 5, and 6 have maximum depths, and the indicated faults have minimum slope and maximum valleyward displacement. The latter characteristic of this type of interpretation may be a partial explanation why

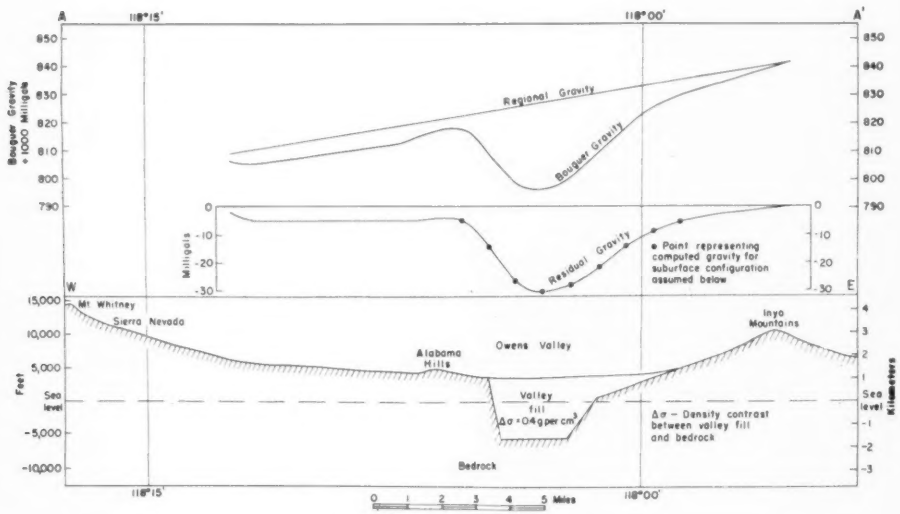

FIG. 4. Analysis of gravity profile A-A'.

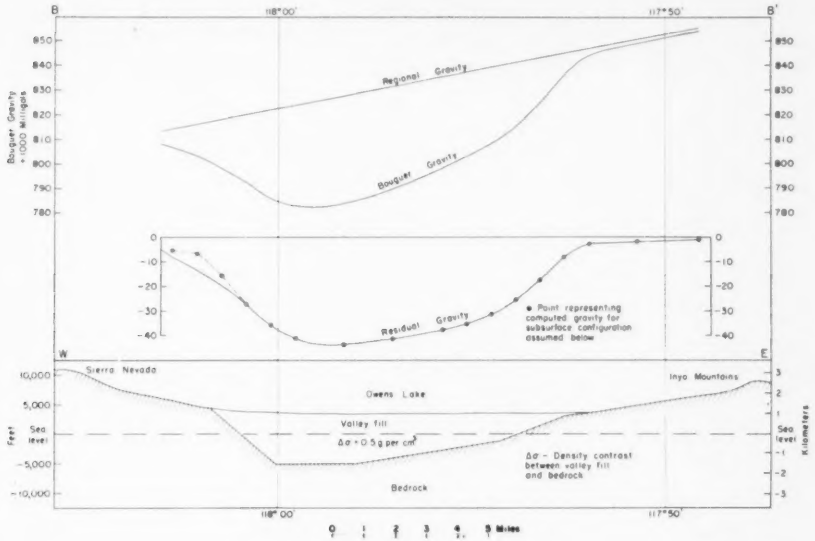

FIG. 5. Analysis of gravity profile B-B′.

boundary faults defined by gravity are sometimes shown with considerable basinward displacement from the mountain walls.

Profile A-A′ (Figure 4) crosses Owens Valley through the center of the gravity minimum east of Lone Pine. A regional gradient of about 2 mgals per mile, negative to the west, was removed from the Bouguer gravity curve. The gravity profile indicates that the bedrock floor has been dropped down more than 9,000 ft below the surface along steeply-dipping border faults. From the seismic experiments by Gutenberg (1932), the dip of the upper part of the western border fault was computed to be greater than 70 degrees. The dip computed from gravity is nearly 80 degrees.

The gravity data (Figure 2) show a local high over the Mesozoic volcanic rocks that comprise the eastern part of Alabama Hills indicating that these rocks have a higher density than the granitoid rocks to the west. If so, the assumed density contrast would locally be somewhat low and the indicated fault inclination would be too high. If the volcanic rocks have considerable volume, the indicated depth would also be too great. An analysis of the gravity curve west of Alabama Hills was not made because the possible inaccuracies and the amplitude of the anomaly are nearly the same.

Profile B-B′ (Figure 5) passes through the gravity minimum in the Owens Lake basin. A regional gradient of 2.4 mgals per mile was removed from the gravity curve. The computed gravity was not matched with the residual gravity curve on the west end of the profile because the field measurements were made in an alluviated embayment that is not representative of the average valley wall. The vertical displacement is more than 8,000 ft, but the bedrock slopes on both sides of the basin are less steep than those near Lone Pine. A small part of the decrease in steepness is caused by the use of a lower density contrast. On the east the sloping bedrock floor suggests that the vertical displacement has been distributed over a wide zone, possibly by warping, although most of the displacement probably took place along the steeper part of the slope.

Profile C-C′ (Figure 6) crosses the southern end of Owens Lake basin in an area in which the gravity field indicates a more complex subsurface structure. There is no evident regional gradient. Most of the vertical displacement seems to occur along two faults on the west side of the valley with the greatest movement probably taking

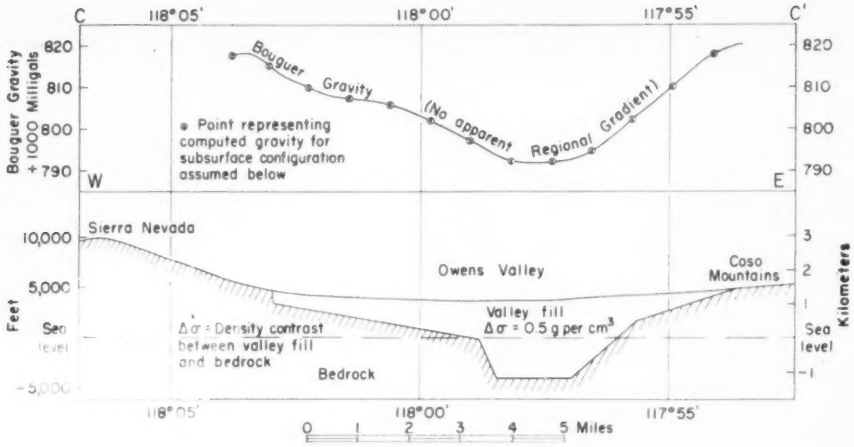

FIG. 6. Analysis of gravity profile C-C′.

place on the easternmost fault. The gravity gradient on the east side of the profile is only defined by a few field measurements and is probably steeper. If so, the bedrock-valley fill interface should also be steeper.

The interfaces that are shown as the subsurface borders of southern Owens Valley are most probably related to faults since they are steeper than their surface counterparts. It is doubtful, however, if the interfaces show the actual locations and inclinations of the faults because the procedure used in the interpretation results in only limiting locations and inclinations for the density interfaces. In addition, any of the bedrock surfaces could be caused by a series of faults of higher inclination that combine in such a manner as to form the slope that is shown. Therefore, the interfaces perhaps best represent the minimum inclination that the contributory faults may have. As pointed out earlier, the locations are probably displaced toward the center of the valley. In some cases the bedrock surface may be a single fault and the probability of this occurring increases as the indicated slope and throw become larger. The very steep interface east of Lone Pine (Figure 4) with a displacement of many thousands of feet strongly suggests a single major fault. The average slope of the six bedrock interfaces is about 50 degrees. Since this is an average of minimum slopes it is concluded that most of the faults that have formed the subsurface borders of southern Owens Valley are steeply dipping.

The depths along B-B′ and C-C′ are greater than the depths at nearby locations that were computed from seismic measurements. This discrepancy indicates that the effective density contrast in the central part of the basin is higher than 0.5 g per cm³. The seismic depth on the east side of the valley opposite Lone Pine is about the same as the depth from gravity at a similar location along profile A-A′. However, the gravity data indicate that the deepest part of the basin is farther to the east. In this narrower part of the valley the gravity data seem to give a better indication of the deepest part of the subsurface bedrock.

ANALYSIS OF NESTED GRAVITY PROFILES

Figure 7 is a series of gravity profiles compiled at intervals of $2\frac{1}{2}$ minutes of latitude along east bearings. The gravity curves have been adjusted for regional gradient and related to the topographic profile so that they reflect, in a qualitative manner, the attitude of the subsurface bedrock. The bedrock configuration has been estimated on the basis of the preceding analyses with allowances being made for differences in anomaly amplitudes, the type of clastic sediments, the width of the valley, and the adjustments in depths indicated by the seismic measurements. The subsurface walls which are shown as vertical were located by an empirical method that approxi-

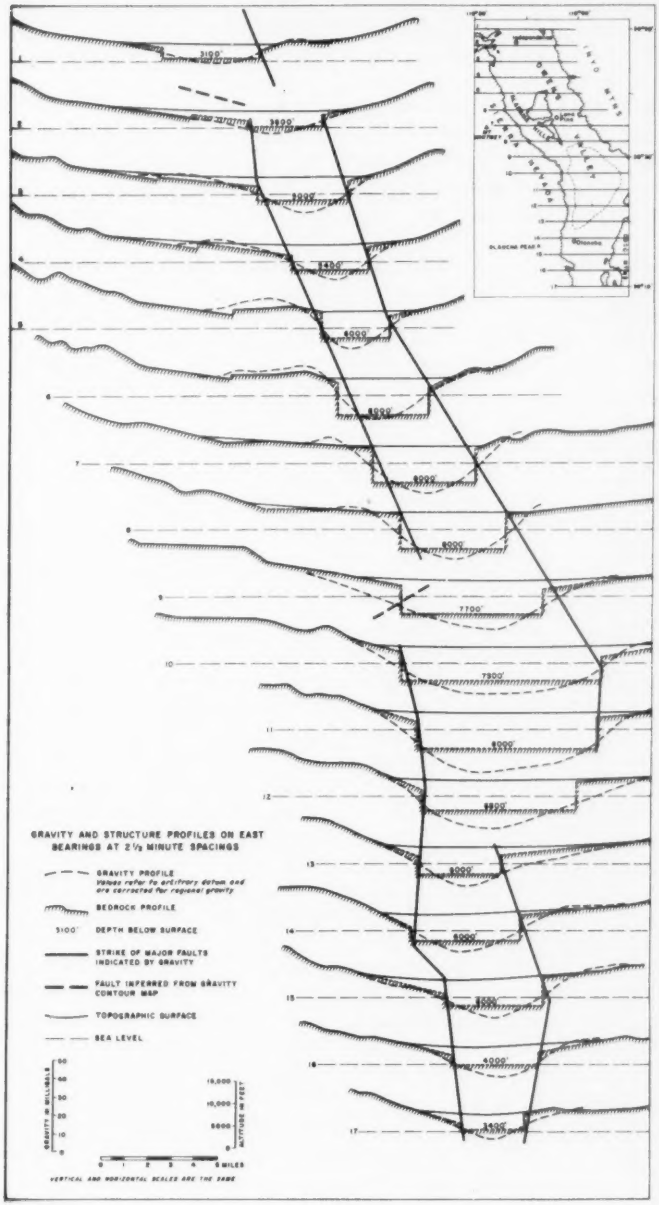
GRAVITY AND STRUCTURE PROFILES ON EAST BEARINGS AT 2½ MINUTE SPACINGS
GRAVITY PROFILE
Values refer to arbitrary datum and are corrected for regional gravity
BEDROCK PROFILE
5100' DEPTH BELOW SURFACE
STRIKE OF MAJOR FAULTS INDICATED BY GRAVITY
FAULT INFERRED FROM GRAVITY CONTOUR MAP
TOPOGRAPHIC SURFACE
SEA LEVEL
GRAVITY IN MILLIGALS
ALTITUDE IN FEET
0 1 2 3 4 5 MILES
VERTICAL AND HORIZONTAL SCALES ARE THE SAME

FIG. 7. Analysis of nested gravity profiles.

mates closely the midpoint of the walls for inclinations greater than 30 degrees. The accuracy of the approximation is subject to the same discrepancies as the previous cross-sections. However, because adjoining sections should be affected similarly, the analysis is useful in defining major trends in the subsurface bedrock even though the lateral position of the trend as a whole may be somewhat in error. The subsurface configuration that is depicted by the sections is one that will give rise to a gravity field similar to that which is present over southern Owens Valley. Although the location of individual faults bounding the valley is not precise, and the overall shape may be expanded or contracted, any analysis of the southern Owens Valley gravity field will retain the essential features of this bedrock configuration.

The fault trends are based on the locations as shown by the sections, and on the continuity of gravity gradients as shown by the contour map (Figure 2). The trends do not cross the west end of profile one or the east end of profile 12 because the gravity gradients are not continuous across these sections. Gravity gradients that have a direction transverse to the main trend of the valley are present at the north and south ends of the bedrock ridge that crops out to form Alabama Hills, and in the area about Olancha. These gradients indicate the presence of corresponding bedrock slopes which are probably the result of faulting.

SEISMIC SURVEY

The seismic velocity of the Cenozoic clastic deposits of Owens Valley is much lower than that of the pre-Tertiary bedrock, so that the Cenozoic and pre-Tertiary interface can be rather reliably defined by seismic-refraction surveys. However, high-velocity beds such as flows and evaporites within the Cenozoic section may make the use of the seismic-refraction method impractical in some areas. Because the cost of seismic work is much higher than that of gravity surveying, and because the geometric requirement of extending each seismic-refraction profile beyond the critical distance is not everywhere easy to satisfy in the narrow Owens Valley trough, the seismic survey was designed mainly as a means of providing depth control for interpretation of the gravity data.

The seismic-refraction profiles described and interpreted in this paper were obtained in June 1958 in a coordinated field program of the U. S. Geological Survey and the Seismological Laboratory, California Institute of Technology.

SEISMIC OBSERVATIONS

Two seismic-refraction profiles (X and Z, Fig. 2) were shot by the U. S. Geological Survey; one long profile (Y) was recorded simultaneously by the U. S. Geological Survey and the California Institute of Technology Seismological Laboratory; and four additional profiles (depth points shown on Figure 2) were shot by the Seismological Laboratory field party. All profiles were shot by conventional seismic-refraction methods in which the geophone spread was in general held fixed and shots recorded at a number of distances from the spread. The method used is equivalent to recording a continuous, reversed geophone spread on the greatest shotpoint to geophone separation.

The velocity layers are determined only beneath the geophone spread (provided the velocity always increases with depth) and it is not known that the same layering is continuous under the entire profile. This assumption was made, however, unless information was available to indicate that the velocities changed laterally along the profile. When the intercept times at all shotpoints plotted along a straight line, indicating that the refracting interfaces were planes along the entire profile, conventional intercept-time computing methods were used (see e.g., Heiland, 1946, p. 521–533). When significant discontinuities were revealed in the intercept times, delay times were determined for each shotpoint and the depths below the shotpoints were computed from the delay times (Nettleton, 1940, p. 250; Barthelmes, 1946; Dobrin, 1952, p. 237–240; Pakiser and Black, 1957). The delay-time method used is approximate in that it does not take adequately into account the changes in dip and velocity of the refracting interfaces along the profile. In view of the uncertainties concerning velocity layering, however, this approximation does not introduce serious errors, and refinements yielding presumably more accurate results can be misleading.

ANALYSIS OF SEISMIC PROFILES

Seismic profile X (Figure 8) east of Owens Lake (Figure 2) was shot in a place where the gravity

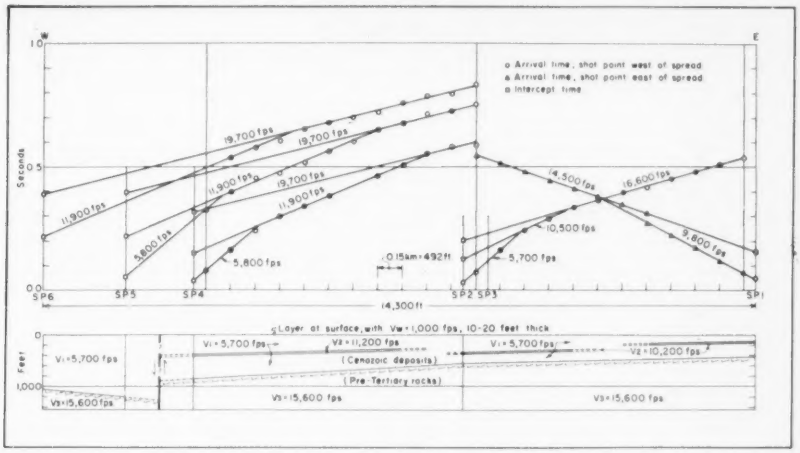

FIG. 8. Analysis of seismic profile X.

data suggest that the pre-Tertiary bedrock should be relatively shallow. Two spreads of 12 geophones, each spread 5,400 ft long, were placed end to end. Seismograms were recorded on the easternmost spread from shotpoints 1 and 2; seismograms were recorded on the westernmost spread from shotpoints 3, 4, 5, and 6, as well as at a shotpoint 11,000 ft west of this spread. The depth as determined from the delay time at this shotpoint was approximately 500 ft greater than that found at shotpoint 5, profile Y. Traveltime data for shotpoints 1, 2, 4, 5, and 6, are given on Figure 8. The arrival times for shotpoint 3 are omitted because no shot instant was recorded on the seismogram.

A low-velocity "weathered" layer 10 to 20 ft thick and with a velocity of about 1,000 fps was assumed to account for the failure of the 5,700 to 5,800 fps traveltime segment to pass through the origin at shotpoints 1, 2, 4, and 5. The 10,200 to 11,200 fps layer was assumed to be thin and discontinuous because the arrivals along that layer were attenuated sharply with distance from the shotpoints. The arrival disappeared entirely at the sixth geophone from shotpoint 1 and at the third geophone from shotpoint 3 (not shown on Figure 8). It was arbitrarily assumed that the layer is 50 ft thick in the interpretation of profile X and that the velocity immediately below this layer is 5,700 fps like the one above it. Therefore, the depths to the 15,600 fps layer (identified as pre-Tertiary rock) in Figure 8 are minimum depths. If the 10,200 to 11,200 fps layer continues downward to the 15,600 fps layer, the depth to that layer would be about 1,600 ft instead of 890 ft below shotpoint 4.

The depths to the 15,600 fps layer below shotpoints 1, 2, and 4 were determined from the intercept-time for a dipping layer. The depths to the same layer below shotpoints 5 and 6 were found by first determining the one-way delay times at each of these shotpoints; from these delay times the depths were computed. An abrupt difference in the intercept time for this layer is noted between shotpoints 4 and 5.

Seismic profile Y (Figure 9) was shot along a line where the gravity data suggest that the pre-Tertiary bedrock is several thousand feet deep beneath shotpoint 1 and relatively much less beneath shotpoint 5 (Figure 2). The U. S. Geological Survey spread (5,400 ft long) and the 7-geophone California Institute of Technology spread (1,200 ft long) were recorded simultaneously to give a full spread length of nearly 8,000 ft. The intercept-time formulas for two dipping layers were used to compute the depths and dip of the 8,600 fps and 15,800 fps layers beneath shotpoints 3, 4, and 7. The failure of the 6,200 fps segment of the traveltime curves to pass through the origin at shotpoints 4 and 7 is explained by the probable presence of a thick weathered layer about 50 ft thick and with a velocity of about

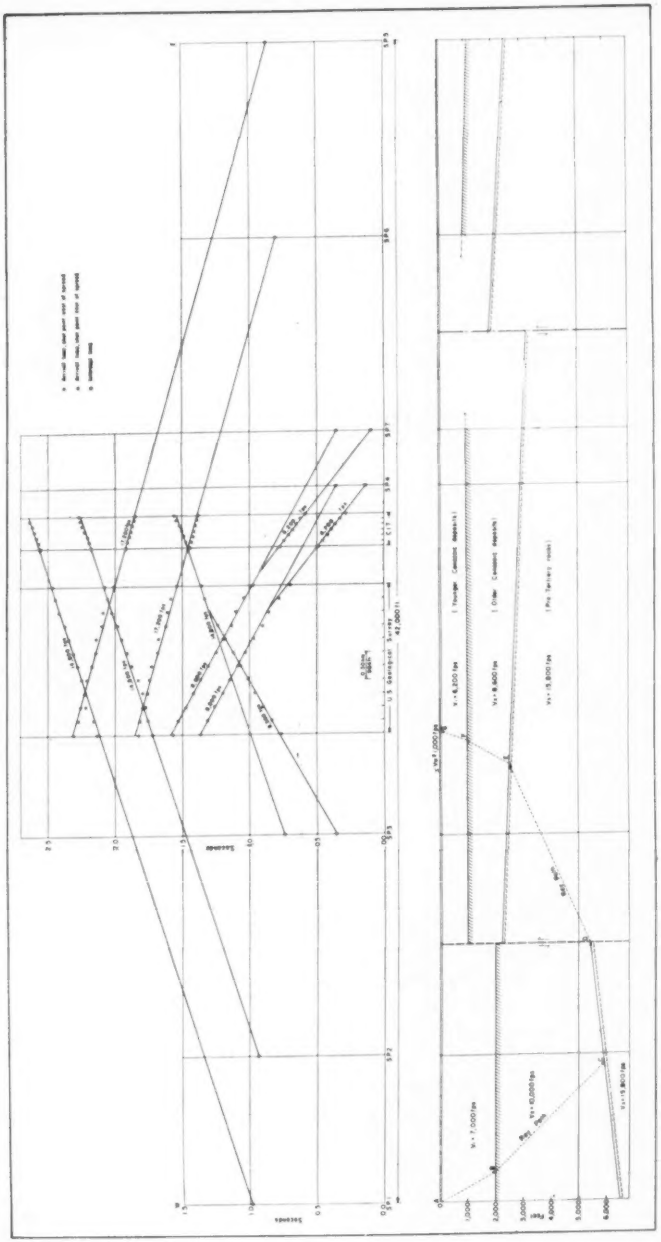

FIG. 9. Analysis of seismic profile Y.

1,000 fps. One-way delay times were computed for shotpoints 1, 2, 5, and 6, and the depths to the 15,800 fps layer beneath those shotpoints were calculated. The intercept times do not plot on a straight line for these shotpoints, so the 15,800 fps layer was assumed to be not plane. The velocity layering beneath shotpoints 1 and 2 is known to be different from that beneath the geophone spread on the basis of a shorter profile shot there. This profile revealed a 7,000 fps layer just below the weathered layer and a 10,000 fps layer at a depth of about 2,000 ft. The velocity layering beneath shotpoints 5 and 6 was assumed to be the same as that beneath the geophone spread.

The depths to the 15,800 fps layer shown in Figure 9 may be in error by as much as 15 percent, but the subsurface configuration cannot differ much from that shown, which, incidentally, agrees very well with that deduced from the gravity data. As a check on the general reliability of this configuration, the ray path (ABCDEFG) which would be followed by a wave traveling from shotpoint 1 to the first geophone of the spread was constructed. The time required to travel this path would be 2.05 seconds; the actual time taken was 2.13. In view of the many uncertainties especially in the thickness of the weathered layer, it seems meaningless to pursue further the possible causes of this 0.08-second discrepancy.

Seismic profile Z (Figure 10) was shot along an east-traveling road just south of Lone Pine. Vincent P. Gianella of the University of Nevada (written communication) had earlier noted that the road is abruptly offset about 16 ft in an apparently left-lateral direction, in the zone of the earthquake fault of 1872 (Whitney, 1872). The position of the road offset falls directly on the trace of a fault as mapped by Willard D. Johnson in 1907 (see Hobbs, 1910). This fault is the easternmost of two important faults along which movement took place in the 1872 earthquake, and evidence for it can still be seen on aerial photographs (Gianella, written communication). The road is a modern oil-surfaced road so it could not have been offset by fault movement, but its 1872 predecessor (perhaps a wagon trail, ditch, or fence line) may have been offset by the earthquake. Whitney (1872) and Holden (1898) reported instances of left-lateral offset of ditches and fences in this general area, but they did not give precise locations. The profile was shot to determine if a fault could be found in the position of the road offset. The seismic traveltime curves and the delay times indicate that the depth to the 5,780 fps layer (assumed to coincide with the water table) increases from about 8 to about 12 ft within 200 ft east of the third geophone from the west, which had been placed in the road offset.

Faults are known to act as ground water barriers or dams that in many places cause depression of the ground water table on the downgradient side of a fault. The surface water from the Sierra Nevada in this area flows eastward. Depression of the ground water table is in the direction and amount that would be expected if a fault actually exists at the road offset.

Depths to the pre-Tertiary bedrock in the Owens Lake basin and east of Lone Pine as determined from seismic-refraction profiling by the California Institute of Technology are similar to the depths that would be inferred from the gravity data (Figure 2). Only the shotpoint locations revealing the greatest depths along each of four profiles are shown on Figure 2.

DISCUSSION OF SEISMIC PROFILES

In the foregoing discussion, no effort was made to relate the layers of different velocities to rock types other than to identify the 15,600 to 15,800 fps layers with pre-Tertiary bedrock, and by implication the shallower layers of lower velocity with Cenozoic valley-fill deposits. A considerable amount of useful geologic information other than structure can, however, be inferred from the seismic data.

The velocity 15,600 to 15,800 fps is characteristic of the granitoid rocks and highly-indurated sedimentary rocks of pre-Cretaceous age that make up most of the pre-Tertiary terrain of the Sierra Nevada and the Inyo Mountains. Therefore, the identification of the layer with this velocity with pre-Tertiary bedrock can be taken as virtually certain, although it is possible that a thick layer of basalt or of evaporites might have the same velocity. The 10,200 to 11,200 fps layer beneath profile X may be a thin layer of basalt such as that which crops out just southeast of the profile, or possibly a bed of evaporites. However, it might also represent deeply-weathered pre-Tertiary bedrock such as Mabey (written com-

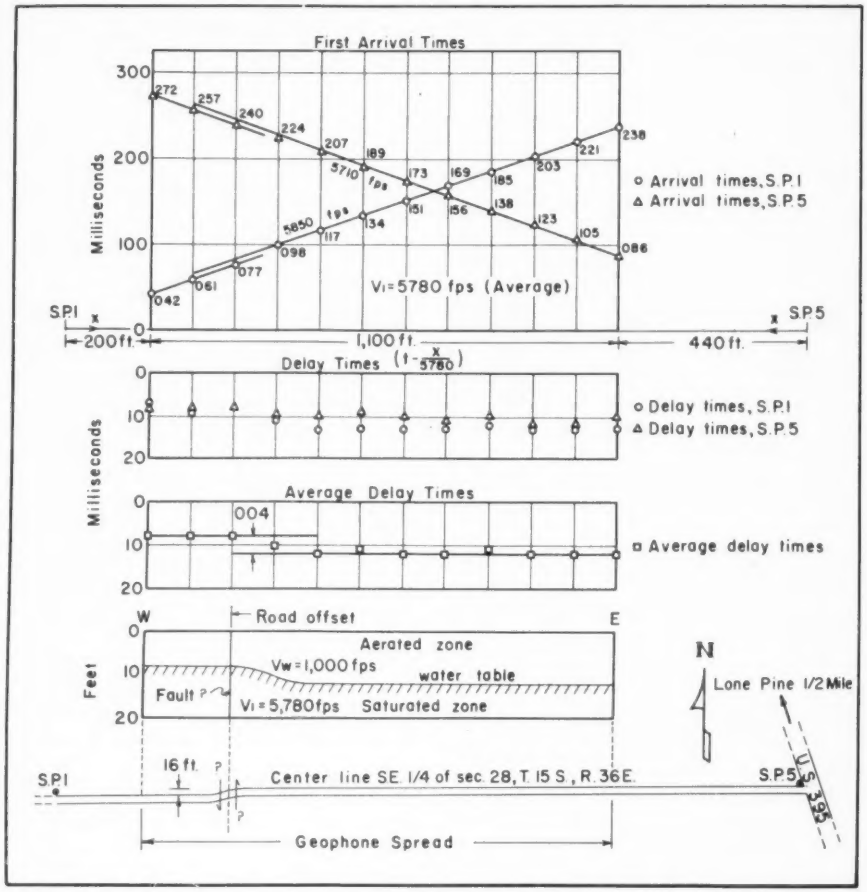

FIG. 10. Analysis of short seismic profile Z crossing offset in road at fault.

munication) has noted in the Mojave Desert and in Saline Valley. The near-surface layer, ranging in velocity from 5,700 to 7,000 fps, is probably composed of unconsolidated or semiconsolidated clastic sediments of late Cenozoic age. The deeper layer, ranging in velocity from 8,600 to 10,000 fps, is probably a rather well-indurated clastic rock of an earlier fraction of Cenozoic time.

The velocity boundary within the Cenozoic section, across which the velocity changes from the 5,700–7,000 fps range to 8,600 fps or more, is characteristic of the Owens Valley region and of Mono Basin (Pakiser, Press, and Kane, 1960), and the boundary is everywhere a fairly sharp one, i.e., the velocity changes from the lower to the higher range in a small interval of depth. In general, the dip of this boundary is in the same direction and less than the dip of the deeper Cenozoic and pre-Tertiary interface, and where it has been displaced by faulting the displacement is invariably less than the displacement of the deeper bedrock. Thus, it can be concluded that faulting and warping have been continuous or repeatedly rejuvenated and essentially concurrent with deposition of the Cenozoic rocks, a conclusion that can be reached independently on the basis of the nature of the fault contacts between the Cenozoic deposits and pre-Tertiary rocks.

The older Cenozoic rocks of higher velocity

must be more highly indurated than the younger deposits of lower velocity, which are probably essentially unconsolidated. The boundary between them may represent either an abrupt change in the rate of deposition or possibly the rate of lithification, or both. Therefore, the velocity boundary may represent a boundary in time in which there was either an abrupt climatic change or renewed uplift of the mountain masses, or both.

The configuration of the Cenozoic and pre-Tertiary interface as determined from the seismic-refraction data for profiles X and Y combined into a single geologic cross-section corresponds very closely with that which would be inferred from the gravity anomaly along this same profile (Figure 11). The gravity is low over the thick section of low density Cenozoic deposits on the west and relatively high where these deposits are thin on the east. The gravity gradient becomes significantly larger above the faults of large throw revealed by the seismic data. A detailed analysis of the gravity anomaly was not made along this line because of the complexity of the structure and of the gravity field.

SUMMARY

The geophysical evidence indicates that the bedrock floor along the axis of southern Owens Valley has been dropped down along steeply-dipping border faults to depths ranging from 1,000 ft above sea level to 5,000 ft below sea level. Thus, the valley block, throughout the greater part of its length, has undergone absolute depression. The strikes of the boundary faults are, in order of decreasing occurrence, northwest, north, and northeast. Movement transverse to the valley trend has taken place along faults whose strike is more nearly east. The relief between the crests of the bordering mountains and the subsurface bedrock floor is nearly 20,000 ft, which is a minimum estimate of the total vertical movement. The present mountain escarpments, although impressive to the eye and very steep topographically, are considerably less steep than the subsurface escarpments. Seismic measurements indicate a fairly sharp change from poorly consolidated to more highly compacted sediments within the Cenozoic valley deposits. This boundary, which has been noted elsewhere in the Owens Valley region (Pakiser, Press, and Kane, 1960), may be caused by a change in the rate of uplift of the nearby mountain masses.

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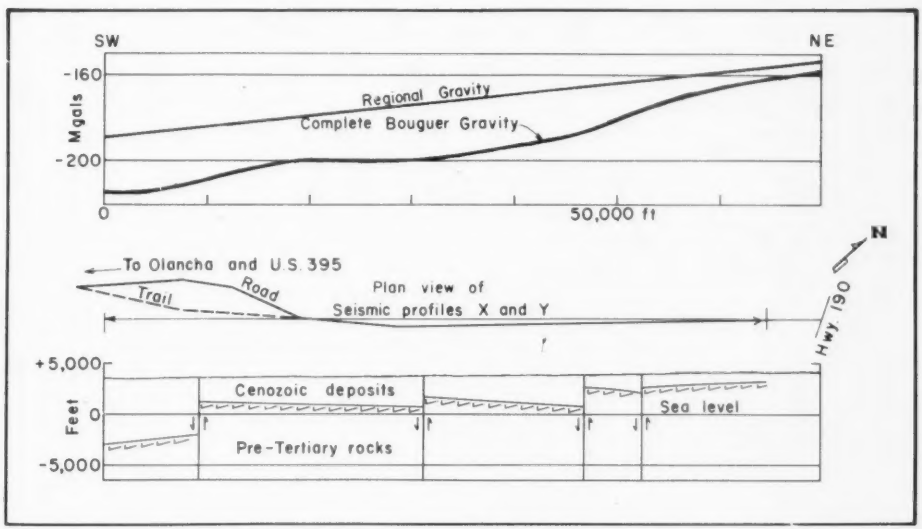

FIG. 11. Comparison of gravity and seismic data along seismic profiles X and Y combined.

Moore, and W. E. Hall, all of the U. S. Geological Survey, for contributing to discussions of the geophysical and geological problems.

The City of Los Angeles Department of Water and Power provided detailed maps and benchmark data along the Los Angeles Aqueduct. The State of California Department of Highways provided access to the plans and profiles for the highways in the area.

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REFERENCES

Barthelmes, A. J., 1946, Application of continuous profiling to refraction shooting: Geophysics, v. 11, no. 1, p. 24–42.

Bateman, P. C., and Merriam, C. W., 1954, Geologic map of the Owens Valley region, California, Map 11 in Jahns, R. H., ed., Geology of southern California: Calif. Dept. Nat. Res., Div. Mines Bull. 170.

Birch, Francis, Schairer, J. F., and Spicer, H. C., eds., 1942, Handbook of physical constants: Geol. Soc. America, Spec. Paper, no. 36, 325 p.

Dobrin, M. B., 1952, Introduction to geophysical prospecting: New York, McGraw-Hill, 435 p.

Duerksen, J. A., 1949, Pendulum gravity data in the United States: U. S. Coast and Geod. Survey Spec. Pub. 244, 218 p.

Gutenberg, Beno, Wood, Harry O., and Buwalda, John P., 1932, Experiments testing seismographic methods for determining crustal structure: Seismol. Soc. America Bull., v. 22, no. 3, p. 185–246.

Heiland, C. A., 1946, Geophysical exploration: New York, Prentice-Hall, 1013 p.

Hobbs, W. H., 1910, The earthquake of 1872 in the Owens Valley, California: Gerl. Beitr. 2, Geophysik, v. 10, p. 352–385.

Holden, E. S., 1898, Catalogue of earthquakes on the Pacific Coast 1769 to 1897: Smithsonian Inst. Misc. Collections, No. 1087.

Hopper, R. H., 1947, Geologic section from the Sierra Nevada to Death Valley, Calif.: Geol. Soc. America Bull., v. 58, no. 5, p. 393–432.

Knopf, Adolph, 1918, A geologic reconnaissance of the Inyo Range and the eastern slope of the southern Sierra Nevada, California: U. S. Geol. Survey Prof. Paper, 110, 130 p.

Lahee, F. H., 1941, Field geology: New York, McGraw-Hill, 853 p.

Mabey, D. R., 1956, Geophysical studies in southern California basins: Geophysics, v. 21, no. 3, p. 839–853.

Mayo, E. B., 1941, Deformation in the interval Mt. Lyell-Mt. Whitney, California: Geol. Soc. America Bull., v. 52, no. 7, p. 1001–1084.

———, 1947, Structure plan of the southern Sierra Nevada, California: Geol. Soc. America Bull., v. 58, no. 6, p. 495–504.

Nettleton, L. L., 1940, Geophysical prospecting for oil: New York, McGraw-Hill, 444 p.

Oliver, H. W., 1956, Nature of isostatic compensation for the Sierra Nevada, California [abs.]: Geol. Soc. America Bull., v. 67, no. 12, p. 1724.

Pakiser, L. C., and Black, R. A., 1957, Exploring for ancient channels with the refraction seismograph: Geophysics, v. 22, no. 1, p. 32–47.

Pakiser, L. C., and Kane, M. F., 1956, Gravity study of the structural geology of Owens and Long Valleys, California [abs.]: Geol. Soc. America Bull., v. 67, no. 12, p. 1724.

Pakiser, L. C., Press, Frank, and Kane, M. F., 1960, Geophysical investigation of Mono Basin, California: Geol. Soc. America Bull. v. 71, p. 415–448.

Swick, C. H., 1942, Pendulum gravity measurements and isostatic reductions: U. S. Coast and Geod. Survey Spec. Pub. 232, 82 p.

Thompson, G. A., and Sandberg, C. H., 1958, Structural significance of gravity surveys in the Virginia City-Mount Rose area, Nevada and California: Geol. Soc. America Bull., v. 60, no. 10, p. 1269–1282.

Whitney, J. D., 1872, The Owens Valley earthquake: Overland Monthly, v. 9, p. 130–140, 266–278.

GEOPHYSICS, VOL. XXVI, NO. 1 (FEBRUARY, 1961), PP. 27-39, 3 FIGS.

THEORY OF NEUTRON LOGGING I*

C. W. TITTLE†

Abstract: An analytical theory of epithermal neutron logging is presented. One-group diffusion theory is applied to the slowing down of neutrons from a point fast neutron source in infinite continuous media, in a single cylinder, and in concentric cylinders representing a fluid-filled borehole and the surrounding formation. Numerical results are given for the epithermal neutron flux in a water-filled hole six inches in diameter, passing through limestone of 10 percent or 30 percent porosity. Preliminary semiquantitative agreement is obtained with the relative response of a commercial logging instrument in the range of 10 to 100 percent porosity.

INTRODUCTION

It is the purpose of this paper to lay a foundation for a practical theory of neutron logging by setting up and solving the equation of elementary diffusion theory for some cases of cylindrical geometry which occur in logging, in the hope that even a restricted theory might be helpful in gaining insight into the neutron logging process and in understanding the behavior of neutron logging devices.

The boundary conditions which exist in a practical neutron logging situation are formidable. Furthermore, no precise and relatively simple physical law, such as Ohm's law as in the case of electric logging, exists for neutron interactions with matter in bulk. Even the simplest theoretical description of the neutron slowing down process—viz., diffusion theory—is more complex than Ohm's law applied to extended media, and there is no guarantee that a theory based on this description will be valid, due to the approximations involved. Nevertheless, in the present work an elementary theory of epithermal neutron logging in certain cases of concentric cylindrical geometry has been developed, based on diffusion theory. In future work, more detailed calculations are planned, and it is hoped that the theory can profitably be refined and extended to other cases. A better comparison with experiment than has been possible with data presently available is also planned.

One of the simpler problems of interest in the logging application is that concerning the spatial distribution of epithermal neutrons due to a point source of fast neutrons. The epithermal neutrons have energies which are just above the energies of thermal equilibrium between the neutrons and the medium. In some neutron logging systems, the epithermal neutrons are actually detected and recorded. In others, thermal neutrons are detected; and in still others, gamma rays due primarily to capture of thermal neutrons by the media are detected and utilized. From the point of view of theory, the processes involving thermal neutrons will be more complex than those involving only epithermal neutrons, because in either case the slowing down of neutrons is involved, but in the case of thermal neutrons the additional diffusion of the neutrons after they have become thermal must be considered. If gamma rays are detected, still other steps —the production and transport of gamma rays in the media of interest—must be included.

In this paper, one-group diffusion theory is applied to the slowing down of neutrons to obtain the distribution of epithermal neutrons in hydrogenous media for three sets of conditions, as follows:

(1) a point fast neutron source in an infinite homogeneous medium;
(2) a point fast neutron source on the axis of a cylinder of finite radius and infinite length;
(3) a point fast neutron source on the axis of two concentric cylinders of finite radius and infinite length.

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ONE-GROUP DIFFUSION THEORY

In searching for a theory of neutron moderation which might be profitably applied to cylindrical geometry, one is led to the choice of one-group diffusion theory as a good one to try, even though there are doubts as to its applicability. Let us first consider the well-known age theory of Fermi, which leads to the following solution for a point source in an infinite homogeneous medium (Glasstone and Edlund, 1952):

$$q = \frac{Q}{(4\pi\tau)^{3/2}} e^{-r^2/4\tau}, \tag{1}$$

where q is the slowing down density in neutrons/cm³ sec, Q is the source strength in neutrons/sec, r is the distance from the source, and τ is the neutron age. The age increases as the energy decreases, the relation being

$$\tau = L_s^2 = \int_E^{E_0} \frac{\lambda_s \lambda_{tr} dE'}{3\xi E'}, \tag{2}$$

where L_s is the slowing down length, E_0 the initial neutron energy, E the neutron energy at which q is evaluated, λ_s the scattering mean free path, λ_{tr} the transport mean free path, ξ the average decrease of $\log_e E'$ per collision, and E' the energy of the neutron as it slows down from E_0 to E. Age theory does not produce good results in hydrogen-containing media such as those of interest in logging.

Extensions of age theory have been proposed by Flügge, Tittle and others (Flügge, 1943; Christy, 1943; Tittle, 1948). In the Flügge-Tittle theory, simple transport considerations are applied to the distribution of first collisions, and age theory is used thereafter. In this theory, the effective source distribution for age theory is

$$Q'(r) = \frac{C}{r^2} e^{-r/\lambda_e}, \tag{3}$$

where C is a dimensional factor proportional to source strength, λ_e the effective mean free path to the first collision with hydrogen, and the source distribution $Q'(r)$ consists of neutrons whose mean energy is E_0/e. This method is capable of producing reasonably good agreement with experimental distributions of epithermal neutrons in extended hydrogenous media, and it can be extended to the computation of thermal neutron distributions. It includes a method of computing the slowing down length (Murray, 1957).

The application of age theory to multiple media, in either its elementary form or its extensions, is fraught with difficulty. The principal complication arises from the fact that as a neutron crosses a boundary between two media, its age changes, because the age is not only a function of energy but also of the properties of the medium (Weinberg and Wigner, 1958).

To overcome this and other difficulties, multigroup diffusion theory has been extensively applied to neutron slowing down problems which involve two or more media (Weinberg and Wigner, 1958). In this theory, the neutrons are regarded as diffusing at a constant energy, jumping to a lower constant energy and diffusing some more, and so on. If enough energy groups are employed, the desired precision can frequently be attained.

In its simplest form, multi-group diffusion theory reduces to one group. Diffusion theory as conventionally conceived applies as a low-order approximation of transport theory, to the case of neutrons of constant energy diffusing through a medium in which they are absorbed as well as scattered. The differential equation of diffusion theory is as follows (Glasstone and Edlund, 1952):

$$D\nabla^2\phi - \frac{\phi}{\lambda_a} + S = \frac{\partial n}{\partial t}. \tag{4}$$

Here ϕ is the neutron flux in neutrons/cm²sec, λ_a the absorption mean free path, D the diffusion coefficient, S the source strength per unit volume, n the neutron density in neutrons per unit volume, and t the time. The neutron flux ϕ is related to the neutron speed v, as follows:

$$\phi = nv. \tag{5}$$

The changes which occur in conventional neutron logging are sufficiently slow that the neutron density may be regarded as constant in time. Hence the time derivative on the right hand side of equation (4) may be set equal to zero. We are specifically interested in a point source. Therefore, at all points except the origin, the source term is zero, and equation (4) may be written

$$\nabla^2\phi - \frac{\phi}{\lambda_a D} = 0. \tag{6}$$

The diffusion length L is defined as $\sqrt{\lambda_a D}$. Thus

$$\nabla^2\phi - \frac{\phi}{L^2} = 0. \tag{7}$$

In the application of interest here, the assumption is made that the absorption of neutrons is negligible until they attain energies quite close to thermal. However, in the use of one-group diffusion theory as a description of slowing down, we regard removal of neutrons from the energy group by slowing down as the equivalent of absorption. In this case, L represents not the diffusion length, but the slowing down length, L_s. Equation (7) remains the same except for the replacement of L_s for L:

$$\nabla^2\phi - \frac{\phi}{L_s^2} = 0. \tag{8}$$

Although L_s may be obtained by use of equation (2) and the definition $L_s^2=\tau$, it is generally more satisfactory to use experimentally-derived values based on the relation (Feld, 1953)

$$6L_s^2 = \overline{r^2} = \frac{\int_0^\infty \phi r^4 dr}{\int_0^\infty \phi r^2 dr}, \tag{9}$$

where $\overline{r^2}$ is the mean square distance of the slowing down distribution. The integrals are evaluated numerically from experimental data, the extrapolation to infinity being made by suitable means. Usually it is assumed that the distribution from a point source goes as

$$\phi = \frac{\text{constant}}{r^2} e^{-r/L'} \tag{10}$$

at large distances, L' being a relaxation length obtained from a plot of the experimental data at distances as large as is practical.

The solution of equation (8) for a point source in an infinite homogeneous medium is (Feld, 1953; Glasstone and Edlund, 1952)

$$\phi = \frac{Q}{4\pi D} \frac{e^{-r/L_s}}{r}, \tag{11}$$

where ϕ, the epithermal flux, is related to the slowing down density q as follows (Hughes 1953): $q=\phi\xi/\lambda_s$; and $D=L_s^2\xi/\lambda_s$. The latter relation is required by the normalization condition that the total number of neutrons in the medium, slowing down through energy E (the epithermal energy) per second, must equal Q, the source strength, since none are assumed lost through absorption. In equation (11), ξ and λ_s are evaluated at the final (epithermal) energy E, and are not average values over the energy interval (E_0, E).

It is interesting to see how closely equation (11) describes the epithermal neutron distribution in water. Figure 1 illustrates the comparison with experiment. The solid curve is the prediction of equation (11), and the experimental points were

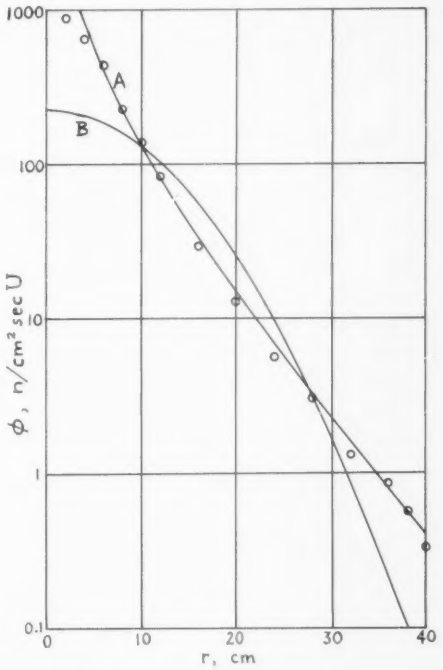

FIG. 1. Comparison of diffusion and age theories with experiment. The neutron source is 300 millicuries of Ra-Be. Experimental points are based on measurements of the indium resonance neutron flux at 1.45 *ev* by Dacey, Paine, and Goodman (1949), adjusted to a source strength of 4.5×10^6 *n*/sec. Curve A: One-group diffusion theory with $L_s=6.8$ cm. $\xi/\lambda_s=1.41$ cm^{-1}. Curve B: Age theory, using the same values of L_s and ξ/λ_s. In the unit for epithermal neutron flux, *n*/cm² sec U, the symbol U stands for the neutron lethargy $(\ln E'/E_0)$. It is to be interpreted as "per unit lethargy interval" in the specification of the unit of flux.

obtained in a large water tank by use of a Ra-Be neutron source and cadmium-covered indium foils which served as epithermal neutron detectors at an effective energy of 1.45 ev. The source strength Q was 4.5×10^6 neutrons/sec. L_s was taken to be 6.8 cm (an experimental value), and ξ/λ_s was 1.41 cm^{-1} as computed from the neutron cross-sections. Curve B in Figure 1 is the prediction of age theory (equation (1)). Agreement with experiment is poor because of the large hydrogen content of water. Except near the source, good agreement is obtained between diffusion theory, Curve A, and experiment, though it is to a large extent undoubtedly fortuitous. Nevertheless, one is encouraged to pursue this elementary theory further. It has, at least, the virtue of describing the slowing down of neutrons as a diffusion process, and it appears that some of the approximations of the theory may be compensatory.

THE CYLINDRICAL MEDIUM

In a medium of finite extent, the escape of neutrons from the surfaces must be taken into account. If the surroundings are effectively the same as a vacuum, no neutrons are returned to the medium once they enter the surroundings, and the latter may be regarded as a perfect absorber of neutrons. It is convenient here to use the concept of the extrapolation distance. If the boundary of the medium is plane, or if its curvature is small, the extrapolation distance (Feld, 1953; Weinberg and Wigner, 1958)

$$l = 0.71\lambda_{tr}, \tag{12}$$

is the distance beyond the boundary at which the neutron flux extrapolates to zero. It is conventional, therefore, to regard the medium as being larger in dimension than the true value by an amount l, and to apply the boundary condition that the flux is zero at this new "boundary." For instance, if there were a point source at the center of a sphere of radius R, one would apply the boundary condition that the flux be zero at a distance $R+l$. The concept of the extrapolation distance greatly simplifies the incorporation of boundary conditions into neutron diffusion theory, and it can be applied not only to the interface between a medium and a vacuum, but also under certain conditions between two media, in which case the value of l depends on the properties of both media (Feld, 1953; Christy, 1943).

Let us apply one-group diffusion theory to a point fast neutron source on the axis of a cylinder of radius a (including the extrapolation distance). The cylinder to be considered is infinite in length. The axis of the cylinder will be designated the z-axis, and the radial distance from the axis will be called r. For the condition of symmetry implied, equation (8) assumes the form

$$\frac{\partial^2\phi}{\partial r^2}+\frac{1}{r}\frac{\partial\phi}{\partial r}+\frac{\partial^2\phi}{\partial z^2}-\frac{\phi}{L_s^2}=0. \tag{13}$$

This equation can be solved by the method of separation of variables. Assume that a solution exists which can be expressed as the product of a function of r only and a function of z only, the functions being designated $R(r)$ and $Z(z)$, respectively. Thus

$$\phi(r, z) = R(r)Z(z). \tag{14}$$

If this solution is substituted into equation (13), the derivatives become ordinary derivatives and the equation can be rearranged as follows:

$$\frac{1}{R}\frac{d^2R}{dr^2}+\frac{1}{rR}\frac{dR}{dr}=-\frac{1}{Z}\frac{d^2Z}{dz^2}+\frac{1}{L_s^2}\cdot \tag{15}$$

The variables have been separated, inasmuch as r appears only on the left and z only on the right hand side of the equation. Since r and z are independent, each side of the equation must be constant; we shall call the constant $-C^2$. Thus we obtain two ordinary differential equations:

$$\frac{1}{R}\frac{d^2R}{dr^2}+\frac{1}{rR}\frac{dR}{dr}=-C^2, \tag{16}$$

and

$$-\frac{1}{Z}\frac{d^2Z}{dz^2}+\frac{1}{L_s^2}=-C^2. \tag{17}$$

These can be rewritten

$$\frac{d^2R}{dr^2}+\frac{1}{r}\frac{dR}{dr}+C^2R=0, \tag{18}$$

and

$$\frac{d^2Z}{dz^2}-\left(C^2+\frac{1}{L_s^2}\right)Z=0. \tag{19}$$

Equation (18) is a form of Bessel's differential equation, whose solution is

$$R = C_1 J_0(Cr) + C_2 Y_0(Cr), \tag{20}$$

where C_1 and C_2 are arbitrary constants, J_0 is the Bessel function of the first kind and zero order, and Y_0 is the Bessel function of the second kind and zero order. For the moment, only real values of C will be considered. Equation (19) is a well-known differential equation whose solution is

$$Z = C_3 e^{-Fz} + C_4 e^{Fz}, \tag{21}$$

where C_3 and C_4 are arbitrary constants and

$$F = \sqrt{C^2 + \frac{1}{L_s^2}}.$$

For reasons of symmetry, the solution along the negative z-axis must be a mirror image of the one along the positive z-axis. It will therefore be sufficient to consider only positive values of z.

$Y_0(Cr)$ is infinite at $r=0$, a condition which is inadmissible; hence C_2 must be zero. The second term on the right in equation (21) goes to infinity as z approaches infinity, a behavior which is likewise incorrect. Hence $C_4=0$. The solution for the epithermal flux ϕ therefore reduces to

$$\phi(r, z) = R(r)Z(z) = C_1 C_3 J_0(Cr) e^{-Fz}, \tag{22}$$

or

$$\phi_n = A_n J_0(C_n r) e^{-F_n z}, \tag{23}$$

where the product C_1C_3 has been replaced by the single constant A_n, and the subscript n has been introduced to denote the fact that various values of C are permissible; and each value of C has associated with it a particular value of F, A, and ϕ. This set of ϕ_n's represents the set of particular solutions of equation (13) which meet the boundary conditions on the z-axis and at infinity. The general solution, subject to these conditions, is the sum of all ϕ_n's:

$$\phi = \sum_n \phi_n = \sum_n A_n J_0(C_n r) e^{-F_n z}. \tag{24}$$

In order to evaluate the C_n, we apply the boundary condition at $r=a$, viz. that the flux is zero. (The radius a includes the extrapolation distance.) This condition is applied to each ϕ_n; thus,

$$J_0(C_n a) = 0, \tag{25}$$

the condition which determines C_n. The function $J_0(x)$ is oscillatory and becomes zero nearly periodically. Let x_n be the set of values of x at which $J_0(x)=0$. Table I lists the first six values of x_n (Jahnke and Emde, 1945).

TABLE I. THE ROOTS OF $J_0(x)=0$ AND THE CORRESPONDING VALUES OF $J_1(x)$

n	x_n	$J_1(x_n)$
1	2.4048	+0.5191
2	5.5201	−0.3403
3	8.6537	+0.2715
4	11.7915	−0.2325
5	14.9309	+0.2065
6	18.0711	−0.1877

Thus,

$$C_n = \frac{x_n}{a}. \tag{26}$$

The next step is to determine A_n. This can be done by expanding the point source into a Fourier-Bessel series in the $z=0$ plane, and equating the series, term by term, to the neutron current through the $z=0$ plane, as obtained from equation (24) and the fact that the current density j and flux ϕ are related as follows (Feld, 1953):

$$j = -D \operatorname{grad} \phi. \tag{27}$$

The point source may be written $Q\delta(r)$. In this expression, Q denotes the source strength, a constant, and $\delta(r)$ is a modified form of the Dirac delta function (Sokolnikoff and Redheffer, 1958), which is defined to be zero everywhere except at $r=0$, where it is infinite in such a way that

$$\int_0^\infty 2\pi r \delta(r) dr = 1. \tag{28}$$

We now expand $\delta(r)$ into a Fourier-Bessel series:

$$\delta(r) = \sum_n B_n J_0\left(\frac{x_n r}{a}\right). \tag{29}$$

To evaluate B_n we form the integral

$$\int_0^a \delta(r) J_0\left(\frac{x_n r}{a}\right) \cdot 2\pi r \, dr = 1, \tag{30}$$

the value 1 arising from the definition of the delta function and the fact that $J_0(0)=1$. If $\delta(r)$ from equation (29) is substituted into equation (30),

except that different symbols m and n are used to denote the index in the two cases, we obtain

$$\int_0^a \left(\sum_m B_m J_0\left(\frac{x_m r}{a}\right)\right) J_0\left(\frac{x_n r}{a}\right) \cdot 2\pi r dr = 1. \tag{31}$$

Now the function $J_0(x_n r/a)$ is orthogonal with respect to the weighting function r in the interval $(0, a)$. This means that every term in the integral of equation (31) will be zero, except the one for which $m=n$. Therefore

$$\int_0^a B_n \left[J_0\left(\frac{x_n r}{a}\right)\right]^2 \cdot 2\pi r dr = 1. \tag{32}$$

This enables us to determine the constant B_n. When the integral is evaluated, we obtain (Jahnke and Emde, 1945)

$$B_n = \frac{1}{\pi a^2 [J_1(x_n)]^2}, \tag{33}$$

where J_1 is the Bessel function of the first kind and first order. Some values of $J_1(x_n)$ are listed in Table I.

We next compute the neutron current density j_n corresponding to each value of n, using equations (27) and (24). We are interested in the current crossing the plane $z=0$. We therefore take the component of the gradient along the z-axis, which has a magnitude $\partial\phi_n/\partial z$. Thus

$$j_n = DF_n A_n J_0(C_n r), \tag{34}$$

where z has been set equal to zero after differentiating. By symmetry, half the neutrons are emitted into each half-space. Hence, combining equations (33) and (29), for each term we equate half the source strength to the current density, to obtain

$$\frac{Q J_0\left(\frac{x_n r}{a}\right)}{2\pi a^2 [J_1(x_n)]^2} = DF_n A_n J_0\left(\frac{x_n r}{a}\right), \tag{35}$$

whence

$$A_n = \frac{Q}{2\pi DF_n a^2 [J_1(x_n)]^2}. \tag{36}$$

Returning to equation (24), we obtain as our final solution for the epithermal neutron flux in a cylinder

$$\phi = \sum_n \frac{Q}{2\pi DF_n a^2 [J_1(x_n)]^2} J_0\left(\frac{x_n r}{a}\right) e^{-F_n z}, \tag{37}$$

where

$$F_n = \sqrt{\frac{x_n^2}{a^2} + \frac{1}{L_s^2}}. \tag{38}$$

This result can be applied to the problem of estimating the size of the blocks of stone to be used in constructing an artificial well for neutron logging studies. Although this calculation neglects the effect of the borehole, the result should be correct as to general magnitude. As an example, we consider a limestone whose porosity of 3 percent is waterfilled. For this medium, it is estimated that L_s^2 is 302 cm^2, by numerical evaluation of the integral in equation (2) using cross-sections modified so as to produce agreement with the experimental values of L_s^2 for water (Munn and Pontecorvo, 1947) and for dry limestone (Tittman, 1955). The value of z is taken to be 38 cm, which is fairly typical of the spacing used in neutron logging instruments. The theoretical results are presented in Table II, where equation (11) has been used for the case $a=\infty$. For this set of conditions, three to five terms of equation (37) were sufficient.

TABLE II. EPITHERMAL NEUTRON FLUX ON THE AXIS AT $z=38$ CM IN WATER-SATURATED LIMESTONE OF 3 PERCENT POROSITY, AS A FUNCTION OF CYLINDER RADIUS a

a, cm	ϕ (relative)
40	0.878
50	0.953
60	0.990
70	0.994
∞	1.000

It is seen that a radius of 60 cm, or about 2 ft, is sufficient to make the flux within one percent of its value for an infinite block. If water lies beyond the limestone, the extrapolation distance is about one inch in this case and need not be considered, within the accuracy of the calculation.

For larger porosities, smaller blocks would suffice, because of the smaller values of L_s.

CONCENTRIC CYLINDERS

The next problem of interest in neutron logging is that of two concentric cylinders, with the source

on the axis. The cylinders are considered to be infinite in length. The inner cylinder represents the borehole, which is taken to be fluid-filled for present purposes. The effect of the logging instrument in displacing the fluid is neglected in order to obtain a first approximation to a real logging situation.

Although the outer cylinder may be infinite in radius, it happens that the case of finite radius is easier to treat, and the solution will be given for that case. The procedure is similar to that employed in the problem of the single cylinder.

Let the radius of the inner cylinder be a and that of the outer cylinder be b. The latter value includes the extrapolation distance. Equation (8) applies in each medium, but L_s is different for the two media, say L_1 for the inner and L_2 for the the cylinder. Thus,

$$\nabla^2\phi_1 - \frac{\phi_1}{L_1^2} = 0; \quad 0 \leq r \leq a \tag{39}$$

$$\nabla^2\phi_2 - \frac{\phi_2}{L_2^2} = 0, \quad a \leq r \leq b. \tag{40}$$

The variables are separated as before, the result for the inner medium being the same, up to the point indicated by equation (23):

$$\phi_{n1} = A_n J_0(C_n r) e^{-F_n z}, \tag{41}$$

where

$$F_n = \sqrt{C_n^2 + \frac{1}{L_1^2}}. \tag{42}$$

A new procedure must be used to evaluate C_n. For this purpose we require the solution for the outer medium, which is the same as equations (20) and (21). We observe that C_2 must be zero as before, but we can no longer eliminate the term in Y_0, because the z-axis is not included in the outer zone. Thus,

$$\phi_{n2} = G_n\left[J_0(P_n r) + H_n Y_0(P_n r)\right] e^{-F_n z}, \tag{43}$$

where the constants have been redefined for convenience, and a different symbol has been used for the coefficient of r. It should be noted that F_n must be the same as for the inner zone, because the z-behavior of a given mode must be the same at $r=a$, when approached from either side. From the procedure of separation of variables, it is seen that

$$F_n = \sqrt{P_n^2 + \frac{1}{L_2^2}}, \tag{44}$$

and by combining equations (42) and (44) we obtain a relation between C_n and P_n:

$$C_n^2 + \frac{1}{L_1^2} = P_n^2 + \frac{1}{L_2^2}. \tag{45}$$

Our solution now contains five unknowns, viz. A_n, C_n, P_n, G_n, and H_n; hence we need four more relations among them in order to evaluate them. (F_n is regarded as known from equation (42) or (44) once the other factors are known.) These four relations are obtained from

(a) the boundary condition at $r=b$, viz. $\phi_{n2}=0$;
(b) the boundary condition on flux at $r=a$, viz. $\phi_{n1}=\phi_{n2}$;
(c) the boundary condition on current density at $r=a$, viz. $j_{n1}=j_{n2}$;
(d) the normalization of the current to the source at the origin, a procedure analogous to the determination of A_n in the problem of the single cylinder.

Applying condition (a), we obtain

$$H_n = -\frac{J_0(P_n b)}{Y_0(P_n b)}. \tag{46}$$

From condition (b),

$$A_n J_0(C_n a) = G_n\left[J_0(P_n a) + H_n Y_0(P_n a)\right]. \tag{47}$$

Condition (c) yields

$$C_n A_n D_1 J_1(C_n a) = P_n G_n D_2\left[J_1(P_n a) + H_n Y_1(P_n a)\right]. \tag{48}$$

The application of condition (d) will be deferred because equations (45) through (48) allow a determination of P_n, C_n, and H_n, which are independent of A_n. First, regard P_n as the variable to be found; eliminate the others from equations

(45)–(48). The result is

$$(49)\qquad \frac{D_2}{D_1}\,\frac{J_0(y)}{yJ_1(y)} = \frac{J_0(x) - \dfrac{J_0(kx)}{Y_0(kx)}\,Y_0(x)}{x\left[J_1(x) - \dfrac{J_0(kx)}{Y_0(kx)}\,Y_1(x)\right]}$$

or

$$(49a)\qquad \frac{D_2}{D_1}\,g(y) = f(x),$$

where

$$(50)\qquad \begin{cases} x = P_n a \\ y = C_n a = \sqrt{x^2 + \dfrac{a^2}{L_2^2} - \dfrac{a^2}{L_1^2}} \\ k = \dfrac{b}{a}\,. \end{cases}$$

Equation (49) must be solved for x (and hence P_n) by numerical methods. A convenient procedure is to compute a table of values of the function on the right hand side of the equation, which is defined as $f(x)$. Similarly, a table of values of $g(y) = J_0(y)/yJ_1(y)$ is computed. The two functions are then graphed as functions of x (after $g(y)$ has been multiplied by D_2/D_1), and the points of intersection yield the values of the roots, x_n. The smallest root corresponds to $n = 1$, etc.

This graphical procedure for finding the roots of equation (49) is illustrated in Figure 2. It is noted that both functions are oscillatory. There are, of course, an infinite number of roots. However, if $k = b/a$ is not too large, it will suffice to consider the first five to ten terms of the series, depending on the value of z.

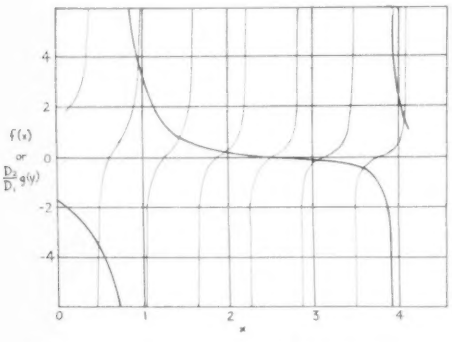

FIG. 2. Graphical method for finding the roots (x_n) of equation (49). The case illustrated is for a 6-inch diameter water-filled hole in limestone of 30 percent porosity, water-saturated. $L_1 = 6.8$ cm. $L_2 = 9.55$ cm, $D_2/D_1 = 0.63$, $b/a = 6$. The light curve is $f(x)$; the heavy one is $D_2 g(y)/D_1$.

We now direct our attention to the determination of A_n. The procedure will be similar to that employed in the case of the single cylinder. Equations (41) and (43) define the flux in the r-interval $(0, b)$. Let us now set up the following expressions:

$$h_{n1} = \sqrt{D_1}\,\mathrm{grad}_z\,\phi_{n1} \qquad 0 \le r \le a$$
$$= \sqrt{C_1}F_n A_n J_0(C_n r) \qquad z = 0 \qquad (51)$$

$$h_{n2} = \sqrt{D_2}\,\mathrm{grad}_z\,\phi_{n2}$$
$$= \sqrt{D_2}F_n G_n\left[J_0(P_n r) + H_n Y_0(P_n r)\right]. \qquad (52)$$
$$a \le r \le b$$
$$z = 0$$

Together, these two equations define a function in the r-interval $(0, b)$ which we shall call $h_n(r)$. If this function is orthogonal with respect to the weighting function r in the interval $(0, b)$, the point source $Q\delta(r)$ can be expanded into a series such that

$$\delta(r) = \sum_n B_n h_n(r), \qquad (53)$$

and the B_n can be determined in a manner analogous to the procedure of equations (29) through (33).

In order to prove orthogonality of the $h_n(r)$, it is necessary to show that for $m \neq n$ (Hildebrand, 1949)

$$\int_0^b r h_n(r) h_m(r)\,dr = 0. \qquad (54)$$

Though the determination of this integral is lengthy, it is straightforward; the calculation will not be reproduced here. The interested reader may prove it with the aid of the fundamental integral (Jahnke and Emde, 1945)

$$\int_0^b x Z_0(k_n x) Z_0(k_m x)\,dx \qquad (55)$$
$$= \frac{b}{k_n^2 - k_m^2}\left[k_n Z_0(k_m b) Z_1(k_n b) - k_m Z_0(k_n b) Z_1(k_m b)\right],$$

where Z_0 stands for J_0 or Y_0 or a linear combination of J_0 and Y_0; and Z_1 stands for J_1 or Y_1 or a linear combination thereof.

The A_n are now determined by the condition that half of the source strength in each mode equals the z-current in that mode integrated over the plane $z=0$. The procedure for the determination of B_n and A_n is analogous to that used for obtaining equations (33) and (36). The result is:

$$\frac{Q}{A_n} = 2\pi D_1 F_n a^2 U_n \cdot \left\{ J_0^2(y_n) + J_1^2(y_n) + \frac{D_2}{D_1}\left(\frac{J_0(y_n)}{Z_0(x_n)}\right)^2 \cdot \left[k^2 Z_1^2(kx_n) - Z_0^2(x_n) - Z_1^2(x_n)\right]\right\} \tag{56}$$

where

$$\left.\begin{aligned} y_n &= C_n a \\ x_n &= P_n a \\ Z_0(x) &= J_0(x) + H_n Y_0(x) \\ Z_1(x) &= J_1(x) + H_n Y_1(x) \\ k &= b/a \\ F_n &= \sqrt{C_n^2 + \frac{1}{L_1^2}} = \sqrt{P_n^2 + \frac{1}{L_2^2}} \\ H_n &= -\frac{J_0(kx)}{Y_0(kx)} \end{aligned}\right\} \tag{57}$$

$$U_n = \frac{J_1(y_n) + \dfrac{D_2 y_n J_0(y_n)}{D_1 x_n Z_0(x_n)}\left[kZ_1(kx_n) - Z_1(x_n)\right]}{J_1(y_n) + \sqrt{\dfrac{D_2}{D_1}}\dfrac{y_n J_0(y_n)}{x_n Z_0(x_n)}\left[kZ_1(kx_n) - Z_1(x_n)\right]}.$$

From equation (41), the solution for the flux in the inner zone is

$$\phi_1 = \sum_n A_n J_0(C_n r) e^{-F_n z}, \tag{58}$$

where C_n is given in terms of P_n by equation (45).

Equation (58) is the solution of the proposed logging problem, inasmuch as measurements of flux are made in the inner cylinder. However, the solution also gives ϕ_2, the flux in the outer zone, by summation of the terms represented by equation (43).

IMAGINARY ARGUMENTS OF THE BESSEL FUNCTIONS

In solving equation (45) for C_n, instances arise in which C_n is imaginary, because usually $L_1 < L_2$; and y will be imaginary. Let $y = iu$, where $i = \sqrt{-1}$ and u is real. These cases of imaginary C_n must be included in the analysis, because $J_0(iu)$ is a real function, sometimes called $I_0(u)$. It is to be noted that although $J_1(iu)$ is imaginary, it appears in equation (49) as a product with iu, the combination being real. This is because (Hildebrand, 1949)

$$iJ_1(iu) = -I_1(u), \tag{59}$$

a real function.

On the other hand, imaginary arguments of the Bessel functions on the right hand side of equation (49), corresponding to points in the outer cylinder, do not occur, as is demonstrated below. In order study this case, it is convenient to return to the differential equation whose solution is equation (43). In the event that P_n^2 is negative, let $Q_n^2 = -P_n^2$, where Q_n is a real number; and let $v = Q_n r$. The solution for the outer medium can then be written

$$\phi_n = G_n\left[I_0(v) + H_n K_0(v)\right] e^{-F_n z}, \tag{60}$$

where I_0 is the Bessel function of the first kind, zero order and so-called imaginary argument, and K_0 is the Bessel function of the second kind, zero order, and imaginary argument. Note that despite this terminology, v is a real number and I_0 and K_0 are both real. Note also that although $J_0(x) = J_0(iv) = I_0(v)$, it is not true that $Y_0(x) = K_0(v)$. The equation which replaces equation (49) is:

$$\frac{D_2}{D_1}\frac{I_0(u)}{uI_1(u)} = \frac{I_0(v) - \dfrac{I_0(kv)}{K_0(kv)}K_0(v)}{v\left[I_1(v) + \dfrac{I_1(kv)}{K_0(kv)}K_1(v)\right]}. \tag{61}$$

The change in sign in the denominator is a result of the fact that $I_0'(x) = I_1(x)$, whereas for the other Bessel functions, $Z_0'(x) = -Z_1(x)$, where Z stands for J, Y, or K.

The functions I_0, I_1, K_0, and K_1 are positive for all positive real values of u and v. Hence the left hand side of equation (61) is always positive. Since $k > 1$, and since I_0 is monotonic increasing

and K_0 is monotonic decreasing $K_0(v) > K_0(kv)$ and $I_0(kv) > I_0(v)$. Therefore, the right hand side of equation (61) is always negative, and the equation can have no real roots.

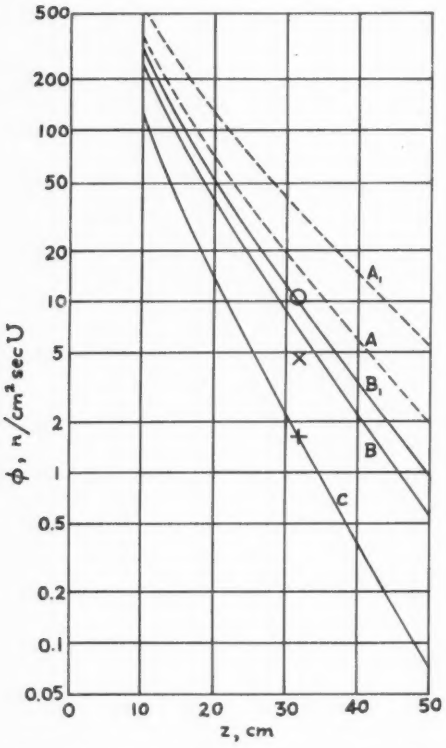

FIG. 3. Examples of theoretical distributions of epithermal neutron flux on the axis of a 6-inch diameter cylinder of water in limestone of 10 percent porosity (curve A) and 30 percent porosity (curve B). The porosity is water-saturated in both instances. The parameters used are listed in Table III. The ratio of radii, $k=b/a$, is 6. The source is Ra-Be with $Q=4.5\times10^6$ n/sec (300 millicuries). For comparison the following curves are included:

Curve A_1: Diffusion theory for an infinite continuous medium consisting of limestone of 10 percent porosity, water-saturated.

Curve B_1: the same, for 30 percent porosity.

Curve C: The same, for water.

+: Response of Perforating Guns Atlas Corporation Model PH-125 epithermal neutron logging instrument in water, normalized to the theoretical curve for water.

×: The same, centered in a 6-inch diameter water-filled hole in limestone of 30 percent porosity.

○: The same, for 10 percent porosity.

THE INFINITE OUTER CYLINDER

The case of the infinite outer cylinder can be approximated by taking $k=b/a$ sufficiently large. For this purpose, the procedure illustrated in Table II can be used to estimate how large k must be. It is desirable to keep k as small as possible in order to obtain rapid convergence of the series. At small porosities and large values of z, it is necessary to use larger values of k.

Numerical examples of the solution to the double cylinder problem, equations (56)–(58), are illustrated in Figure 3. In the examples, k was sufficiently large to make the outer cylinder effectively infinite for the values of z employed. It is seen that the neutron distribution in the water-filled hole lies between those predicted by the theory for infinite homogeneous media of water and of limestone. Semiquantitative agreement with the response of the Perforating Guns Atlas Corporation Model PH-125 epithermal neutron logging instrument (Rabson, no date) is indicated. The effects of the finite size of the instrument have yet to be elucidated. Undoubtedly the internal structure, including the radiation shielding arrangement, has a strong influence.

DETECTION OF GAS

If a substantial amount of invasion of the formation by liquid filtrate from the borehole fluid occurs, the presence of gas may be masked. The methods described in this paper can be applied to a theoretical study of invasion and gas detection by applying an albedo boundary condition (Feld, 1953; Christy, 1943) at the interface between the invaded zone and the gas zone, the effect of the gas being taken into account by proper selection of the extrapolation length.

A discussion of this application, together with the presentation of further examples of the application of this theory and a procedure for determining the slowing down length L_s and the diffusion coefficient D for media of interest in well logging, is planned in subsequent work.

CONCLUSIONS

An analytical theory of epithermal neutron logging has been developed by applying one-group diffusion theory to the slowing down of neutrons from a point fast neutron source in concentric cylindrical media. Detailed comparisons with

experiment remain to be drawn, but preliminary semiquantitative agreement has been obtained with the relative response of a commercial logging instrument in the range of 10 to 100 percent porosity.

ACKNOWLEDGMENTS

The invaluable assistance of the Computing Laboratory at Southern Methodist University is acknowledged. Dr. Paul Minton, Director of the laboratory, made possible the computation of tables of functions $f(x)$ and $g(y)$ on the Univac 1103, and Mr. Charles Brown wrote the programs. Mr. L. Scott Allen contributed greatly to this effort by checking the mathematics and by making the calculations for Figure 3. The financial assistance of the Western Company is gratefully acknowledged.

TABLE III. PARAMETERS FOR FIGURE 3

Curves	L_1, cm	L_2, cm	D_1, cm	D_2, cm
A, A_1	6.8	13.3	65	31
B, B_1	6.8	9.55	65	41
C	6.8	—	65	—

APPENDIX

THE RUSSIAN LITERATURE ON THE THEORY OF NEUTRON LOGGING

Mr. J. A. Czubek, of the Academy of Mining and Metallurgy, Cracow, Poland, has kindly supplied the following summary of the Russian literature on the theory of neutron logging. The summary was translated by Dr. K. Przewlocki of the same institution. This body of literature is rather extensive; however, the problem presented in the present paper is not covered by it.

Bulashevich (1948, 1951) and Kantor (1955) have considered neutron-neutron and neutron-gamma logging in infinite, homogeneous media. They discuss the effects of "short" and "long" spacing between source and detector. The developments are based on the fundamental theories of neutron slowing down and diffusion (Glasstone and Edlund, 1952). Equations for the thermal neutron distribution are given.

Glauberman and Talianskyi (1957) and Talianskyi (1958) have applied the two-group diffusion approximation to the distribution of neutrons. The first of these two papers considers a point source on the axis of a borehole passing through an infinite medium. The second paper considers two strata separated by a plane boundary but not cut by a borehole. No numerical results are given.

Temkin (1957) gives a solution of the kinetic equation for neutrons in the form of a series of functions, by finding the Green's function of a certain integro-differential equation. The borehole is not considered, and there are no numerical results.

The Russian Academy of Science (Akademiya Nauk SSSR, 1958) published the Proceedings of the national conference which was held in Moscow in April, 1957, concerning the application of isotopes and radiation. One session of this conference was devoted to the exploration and production of useful minerals. The book which constitutes the proceedings of this session contains 34 papers, most of which are devoted to nuclear logging in its various aspects. A set of abstracts in English (U. S. Atomic Energy Commission, 1958) is available. One of these papers, "The Theory of Neutron Well Logging Methods," by S. A. Kantor and A. Ya. Temkin, considers the theory of neutron moderation in cylindrical media and in continuous media.

Barsukov et al. (1958) have written a rather thorough book on nuclear well logging. Chapter VIII , by O. A. Barsukov and K. A. Barsukov, is entitled, "Fundamental Theories of Neutron-Neutron and Neutron-Gamma Methods of Investigating Boreholes." Among other things, this chapter gives a solution of two-group diffusion theory for a point source on the axis of a borehole cutting through an infinite medium. Some numerical results are given.

Kantor (1958) gives a solution of the kinetic equation in cylindrical symmetry through the Fourier integral, by assuming a value for the neutron mean free path. An estimate of depth of investigation is given. This paper extends the work of Kantor and Temkin mentioned above (Akademiya Nauk SSSR, 1958).

Kulinkovich (1959) considers a problem similar to that of Glauberman and Talianskyi (1957), but for only one neutron group and for many cylindrical boundaries (representing borehole, casing, cement, formation). The solution is in the form of a Fourier integral for the whole space. There are no numerical results.

Temkin (1959) gives a solution of the neutron kinetic equation for a homogeneous medium. Curves for different rocks are calculated. A rather simple equation is given for the density of epithermal neutrons as a function of distance, source strength, mean free path, average value of the ratio of scattering cross sections for protons and heavy nuclei, and water saturation of rocks. Theoretical calculations are compared with the experimental results of Tittle, Faul, and Goodman (1951).

Kantor (1959) applies the results of a previous paper (Kantor, 1958) to the determination of the epithermal neutron distribution in a medium cut by a borehole. The author calculates the moments of the distribution function. Theoretical results are compared with experiment.

A recent book entitled "Nuclear Geophysics" was published by the Soviet Technical Publishing Agency (Gostoptekhizdat, 1959). It is a collection of various papers, consisting mainly of experimental work on nuclear logging. One of the papers, by Zolotov, shows the deviations of the theory of Bulashevich (1951) from reality. Much of the work reported deals with activation logging, neutron activation analysis, and the use of the neutron generator in boreholes.

The Russian Academy of Science (Akademiya Nauk SSSR, to be published) sponsored another national conference in Moscow in March, 1959, on the applications of isotopes and radiation. Many papers on nuclear well logging were presented. The Proceedings, when available, should be of considerable interest.

Talianskyi, Bilenkin, and Dragan (1960) have extended the work of Glauberman and Talianskyi (1957). Two-group diffusion theory is applied to the determination of the thermal neutron density in a mud-filled borehole traversing limestone of various porosities (0, 10, 20, and 30 percent), oil filled. Numerical results are given for points on the axis at 10, 20, 30, 40, and 50 cm, for borehole radii of 0, 10, and 15 cm. For the last-mentioned borehole radius, only porosities of 0 and 30 percent are considered.

REFERENCES

Note: The Russian papers are in Russian unless otherwise stated.

Akademiya Nauk SSSR, 1958, Exploration and production of useful minerals (Proceedings of the all-union scientific-technical conference on the application of radioactive and stable isotopes and radiation in the national economy and science, 4–12 April, 1957): Gostoptekhizdat, Moscow.

Akademiya Nauk SSSR, to be published; similar to previous reference; conference was held in Moscow, 1–7 March, 1959.

Barsukov, O. A., et al., 1958, Radioactivity methods of investigating oil and gas boreholes: Gostoptekhizdat, Moscow.

Bulashevich, Yu. P., 1948, Theory of neutron logging as applied to exploration of oil and coal deposits: Izv. Akad. Nauk SSSR, Seriya Geografich. i. Geofizich., vol. 12, no. 2, p. 155–168.

Bulashevich, Yu. P., 1951, On the theory of neutron logging: Izv. Akad. Nauk SSSR, Seriya Geofizich., no. 3, p. 31–36.

Christy, R. F., 1943, Lecture notes on neutron diffusion: MDDC-1175, Lecture Series in Nuclear Physics, U. S. Government Printing Office, Washington, D. C.

Dacey, J. E., Paine, R. W., and Goodman, C., 1949, Nuclear shielding studies III. Shielding properties of various materials against neutrons and gamma rays: Technical Report No. 23, Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Mass.

Feld, B. T., 1953, The neutron: Part VII of Experimental Nuclear Physics, v. 2, edited by E. Segrè, John Wiley and Sons, Inc., New York.

Flügge, S., 1943, Über die raümliche Verteilung abgebremster Neutronen: Phys. Zeits., v. 44, p. 445–455.

Glasstone, S., and Edlund, M. C., 1952, The elements of nuclear reactor theory: D. Van Nostrand Company, Inc., Princeton, N. J.

Glauberman, A. E., and Talianskyi, I. I., 1957, Neutron flux distributions in media separated by a cylindrical boundary: Atomnaya Energiya, v. 3, no. 7, p. 23–27. Also available in English in J. Nucl. Energy, v. 8, p. 84–90 (1958).

Gostoptekhizdat, 1959, Nuclear geophysics: Symposium of Articles: Moscow.

Hildebrand, F. B., 1949, Advanced calculus for engineers: Prentice-Hall, Inc., New York. A valuable discussion of Bessel functions is given. The modern notation is compared with that of Jahnke and Emde.

Hughes, D. J., 1953, Pile neutron research: Addison-Wesley, Cambridge, Mass.

Jahnke, E., and Emde, F., 1945, Tables of functions (4th edition): Dover Publications, New York.

Kantor, S. A., 1955, Fundamental theory of neutron logging: Prikladnaya Geofizika, vypusk 13, no. 3, Gostoptekhizdat, Moscow.

Kantor, S. A., 1958, On the depth of investigation of rocks by neutron-neutron logging: Prikladnaya Geofizika, vypusk 21, p. 111–133.

Kantor, S. A., 1959, On the nature of the influence of borehole diameter on the records from a neutron-neutron instrument: Prikladnaya Geofizika, vypusk 23, p. 174–192.

Kulinkovich, A. E., 1959, On the distribution of thermal neutrons under borehole conditions: Prikladnaya Geofizika, vypusk 22, p. 187–201.

Munn, A. M., and Pontecorvo, B., 1947, Spatial distribution of neutrons in hydrogenous media containing bismuth, lead, and iron: Can. J. Research *25A*, p. 157–167.

Murray, Raymond L., 1957, Nuclear reactor physics: Prentice-Hall, Inc., New York.

Rabson, W. R., no date, Porosity evaluation charts for the PH-125 neutron/neutron Log: Perforating Guns Atlas Corporation, Houston, Texas.

Sokolnikoff, I. S., and Redheffer, R. M., 1958, Mathe-

matics of physics and modern engineering: McGraw-Hill, New York.

Talianskyi, I. I., 1958, On the distribution of neutrons in media of known properties with plane boundaries: Atomnaya Energiya, v. 4, no. 4, p. 372–374.

Talianskyi, I. I., Bilenkin, B. F., and Dragan, J. P., 1960, On the theory of neutron well-logging: Prikladnaya Geofizika, vypusk 25, p. 223–233.

Temkin, A. Ya., 1957, Method of approximate solution of the kinetic equation for neutrons: Prikladnaya Geofizika, vypusk 17, p. 211–230.

Temkin, A. Ya., 1959, Certain methods for solving theoretical problems of neutron logging: Prikladnaya Geofizika, vypusk 23, p. 141–173.

Tittle, C. W., 1948, The slowing down and diffusion of neutrons in hydrogenous media: Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, Mass. Issued as NP-1418 by Technical Information Division of AEC, Oak Ridge, Tenn., 1949.

Tittle, C. W., Faul, H., and Goodman, C., 1951, Neutron logging of drill holes: The Neutron-Neutron Method: Geophysics, v. 16, no. 4, p. 626–658.

Tittman, Jay, 1955, Moderation of neutrons in SiO_2 and $CaCO_3$: J. App. Phys., v. 26, p. 394–398.

U. S. Atomic Energy Commission, 1958, All-union conference on the application of radioactive and stable isotopes in the national economy and science (Abstracts of Papers and Plenary Session Papers) AEC-tr-2925, Technical Information Service Extension, Oak Ridge, Tenn.

Weinberg, A. M., and Wigner, E. P., 1958, The physical theory of neutron chain reactors: University of Chicago Press, Chicago, Ill.

GEOPHYSICS, VOL. XXVI, NO. 1 (FEBRUARY, 1961), PP. 40–44, 11 FIGS.

THE ELECTRONIC COMPUTER AND GEOPHYSICS*

L. S. MORRISON† AND ROBERT WATSON†

Abstract: With the advent of electronic computers a revolution in data handling has been brought about. As yet few people outside of scientific research or accounting fields are familiar enough with these computers to know how they can be applied in their particular type of work.

Electronic computers consist of three basic elements: an operations register, a digital computer and a memory unit.

The memory unit retains information in numeric form in locations that are identified by a coordinate system. Data stored in memory may be retrieved and processed in the digital computer and the results of the computation may be stored for later use. Computations are carried out in the binary or two-digit number system.

The operations register controls the operation of the digital computer and the memory unit and acts as a link between the intent of the programmer and the internal operation of the system.

An object, given the proper code numbers describing its shape, size, color, etc., can be identified from other objects by comparison of code numbers. The speed and ability of electronic computers to compare and identify makes possible the solution of very exacting problems that otherwise would be humanly next to impossible from time considerations.

Electronic computers have been used in geophysical exploration to compute and contour derivative maps of gravity and magnetic data. They have been used to reduce gravity data to datum, compute interval and average velocities from velocity profile data and have been used to solve many non-recurring problems.

THE ELECTRONIC COMPUTER AND GEOPHYSICS

A revolution in data handling is taking place. We are aware of it in dramatic form when we read about such things as the guidance of various types of missiles once they have left their launching pads. We are aware of it in personal matters such as how quickly our pay check is computed in spite of the vast number of deductions. Yet, relatively few people other than those in accounting or in scientific research are familiar enough with electronic computers or "brains" to know how they can be applied in their particular type of work.

Before we can discuss the use of computers in everyday geophysical operations we must have some notion of how they operate. Let's take, for example, the image of an object, say, an apple (Figure 1).

When we see an apple for the first time, we form an image of it in our mind. We might notice that its shape is round, its color red and it has a stem on top. Someone tells us it is an apple so we assign the name "apple" to the box in our brain where the image is stored. It now has an address so that we can produce the image of this object merely by recalling the word "apple." As we become more familiar with apples we store additional information about them in the address labeled "apple"—taste, texture, size, variations in color and shape, seeds, etc. Then one day we are shown a plum. We compare it with what we know is round, red and has a stem, and deduce that it might be an apple. But does it have all the other properties of an apple? We test it and see that it does not. So the process of accumulating information (knowledge) continues until we have a complex cross-indexed set of images and facts stored in our brain. This is what we call memory.

Electronic computers consist of three major

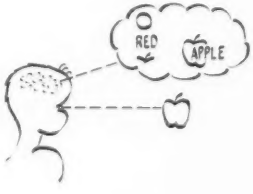

FIG. 1

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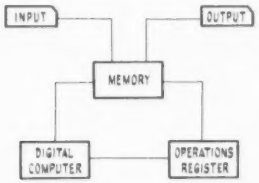

FIG. 2

components that might be schematically shown as an operation's register, a digital computer, and a memory unit (Figure 2).

There are currently three types of memory units; the rotating drum, the disk, and the solid state or core storage. These units have magnetizable areas on them called "bits" where facts that can be represented by numbers may be stored. Each bit has a coordinate that describes its position in the memory unit. Depending on what bits are magnetized, digits from 0 through 9 may be represented.

The total number of digits that may be stored in a memory unit varies with the model and manufacturer. Rotating drum memory units may store from 20,000 digits as used in the IBM 650 computer to 180,000 digits as in the Remington Rand "Univac." Disk storage units consist of a set of flat, circular grooved disks stacked in a column. Mechanical arms search the grooves for information. Each disk may contain as many as 120,000 digits. The IBM 355 "Ramac" or "Random Access" unit is made up of fifty such disks making a total of 6 million digits. Disk storage units are generally used as accessory equipment to drum or core storage units.

Core storage units, unlike disk and drum units, have no moving parts. Data is placed in memory and retrieved electrically rather than electromechanically.

The calculator in an electronic computer is a high speed digital type. Unlike a desk calculator a digital computer uses a two digit number system rather than a ten digit system. Numbers are represented by combinations of 0 and 1 instead of combinations of 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9. The two digit scale or what is known as the "binary" system, is more efficient electronically than our ordinary scale of ten, or decimal system, because a number can be represented by a series of positive and negative charges (Figure 3).

Arithmetic operations are accomplished by simple addition and subtraction of digits and the procedure is the same in binary form as in decimal form. Digits may be added at speeds ranging from 50,000 additions per second to over 120,000 digits per second depending on the type of computer.

The digital computer is controlled by the memory through an operations register that responds when receiving certain impulses from the memory. These controlling impulses may be generated from combinations of numbers stored in memory that cause the computer to operate on other information in the memory in a specific way. These combinations of numbers are called program instructions. With these program instructions the computer can be made to multiply, divide, add, or subtract information that is stored in various locations in the memory. Organizing the instructions necessary for a computer to solve a particular problem is called programming. These instructions are usually put on punched cards or tape and fed into the memory. Next, the data to be processed are fed into the memory in a similar manner. The computer is then sent to the memory location of the first program instruction and from there it follows faithfully the instructions the programmer has placed in memory. The results of the program are generally punched out in cards or on tape and are then printed with an automatic printer.

The operations register also acts as a link between the intent of the programmer and the internal operation of the system. The impressive array of flashing lights on the console or control panel is a part of the operations register. If the machine is stopped at any place in the program, from the display of lights, the operation being performed can be determined. This is important to the programmer in testing a new program for mistakes, as it allows him to systematically follow the steps of the program and "debug" it.

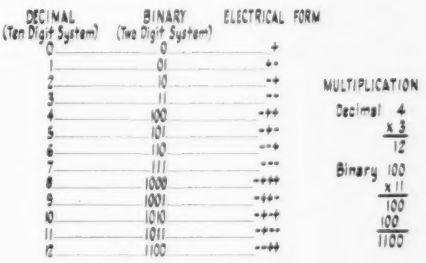

FIG. 3

SHAPE CODE	COLOR CODE	OTHER PROPERTY CODE
Round 1	Brown 1	Made of Leather 1
Triangular 2	Red 2	Has a Stem 2
Square 3	Black 3	Has a Handle 3

FIG. 4

Besides being able to perform the basic arithmetic operations such as multiplication and division the computers can be made to answer questions either yes or no. This is done by testing to see if a number is either plus or minus or zero or not zero. The value of this can be easily demonstrated. Suppose we set up the table, shown in Figure 4, to list a few properties that an object might have. We can give each property a code number. If we have classified an object numerically by its properties and punched this information into cards or tape, then if this object enters into some sort of calculation in the computer, the computer can recognize it and identify it.

We can assume the table listing the properties is already stored in memory. Identification of an object could be accomplished in the following way (Figure 5):

We might first want to know: What is its shape? To answer this we would ask: Is it round? We would then want to know: What is its color? Is it brown? Is it red? Is it black? If it is round and black we might ask: Does it have a handle? If it does, we may conclude it is a frying pan.

Let's give an object the code number 1, 2, 2 from Figure 4 meaning the object is round, red and has a stem. Looking at Figure 6 we see that by comparing the code number of the object for shape with the code number of the table stored in memory under "round" that $1-1=0$. This means that the digit representing the shape of the object is the same as the digit representing the shape "round" in the table stored in memory. Therefore, the object is round.

Next we ask: Is it brown? $2-1\neq 0$, therefore, the object is not brown. Is it red? $2-2=0$, so it is red. Comparing its next property we see upon asking: Does it have a stem?, that $2-2=0$, therefore it has a stem and is an apple.

The object having been identified, it may be given another code meaning apple and from there the computer continues toward the solution for which it has been programmed. Instead of apples and frying pans we might have wanted to identify a certain reflection or a particular formation.

As can be imagined from the foregoing example, the more complex the decision to be determined or the problem to be solved, the more questions have to be answered. This ability of electronic computers to compare makes it possible to solve very exacting problems that from time considerations would be humanly next to impossible. Problems ranging from the solution of simultaneous equations of 40 to 50 variables to the problem of determining the best bid on a sale of federal lands have been solved on electronic computers.

Electronic computers are not only very versatile but are very fast and can be made to repeat an operation over and over again. This is primarily why they have been so widely accepted in the accounting field.

Perhaps we can now ask: How can we apply electronic computers to geophysical exploration for oil? To answer this, let us look at a few applications.

We have all seen or at least heard of 2nd derivative maps made from magnetic total intensity maps or from Bouguer gravity maps. There are many ways to construct derivative maps but most of them require the data to be gridded in some manner and a weighted average of values surrounding a center point computed and this average subtracted from the value at the center point. This is a monotonous and time-consuming process and consequently once a grid spacing is chosen, very rarely are additional derivative maps

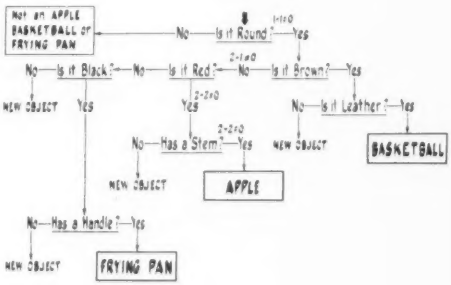

FIG. 5

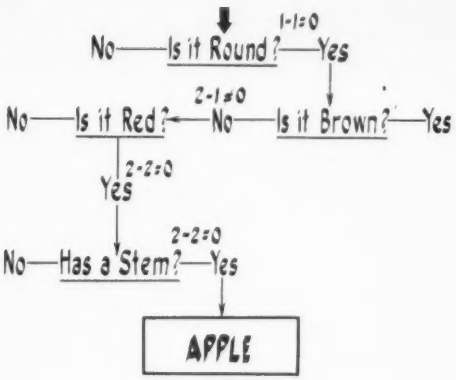

FIG. 6

made from other grid spacings. To alleviate this problem a program was written that computes derivative maps for five different grid sizes. This is done at the rate of one derivative computation every 0.4 second. However, we then had five maps to post and contour instead of one, creating another time and manpower problem. To get past this bottleneck a method of posting the data with an IBM 407 accounting machine was devised which posts the data in ten-inch wide strips at the rate of 150 points per minute (Figure 7). The decimal point is the location of the grid point. The strips are then spliced together and photographically reduced to any scale desired. All that remains to be done is the contouring.

Since contouring consists largely of interpolating between points it seemed likely that even this sacred task could be relegated to the computer. A program was devised whereby the output from the derivative program could be fed into the electronic computer and an interpolation made between data points so that on the printed map digits from 0 to 9 representing contour values would appear one tenth of an inch apart (Figure 8). When the digits change, for example, from 7's to 8's, it means the contour value has changed by an amount of 10. Figure 9 is the same area contoured in the conventional manner. As can be seen the center of the map is a closed high.

The digits decrease as you go out from the center from 0 to 9 to 8, 7, 6, 5, and so on

A more striking example of this type of contouring was made from magnetic data that were punched into cards and processed with a computer (Figure 10 and 11). Interpolated values were computed each tenth-of-a-unit distance apart in east-west rows. The digit in the 10's position of each resulting interpolation was punched into the proper column on a punch card. Of the 80 columns in each card, ten were used for identification purposes and 70 columns contained digits from 0 to 9 that represented the magnitude of the magnetic values within a 10-gamma range at each interpolated point. Therefore, when the values changed from, say 129.1 to 130.4, the digit 2 would appear adjacent to the digit 3 indicating

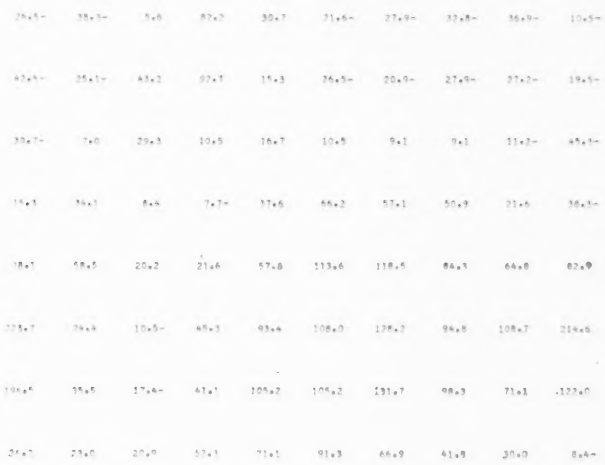

FIG. 7

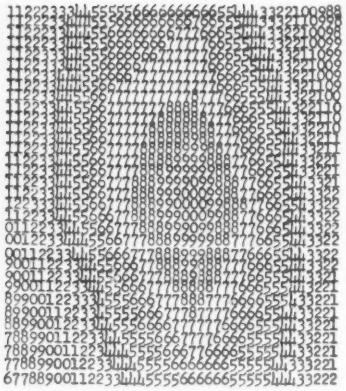

FIG. 8

the 130.0 contour should go between those two points.

Since interpolated points were computed at every tenth-of-a-unit distance each card represented a row of data 7 units wide. Successive rows spaced one tenth-of-a-unit distance north-south were computed. These were printed with the IBM 407 resulting in one "page" of contoured data. The IBM 407 can be made to print 10 digits per inch vertically and horizontally with but a minor alteration of the paper drive mechanism. With this adaption the contoured "pages" were printed seven inches wide with digits one-tenth of an inch apart. The pages were then spliced together and photographically reduced.

In Figures 10 and 11 the contour interval is 10 gammas. Each map is about 96 miles or 16 townships across, and they required about 3 hours per map to contour and print them. It would probably

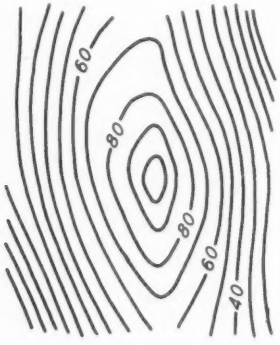

FIG. 9

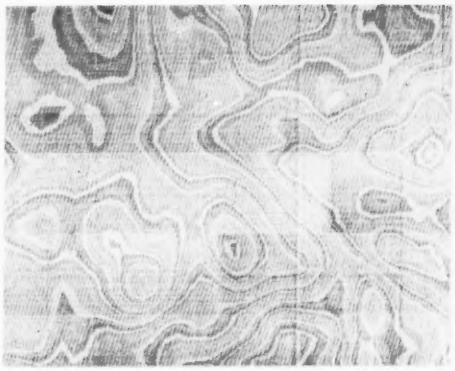

FIG. 10

take a geophysicist at least three days to contour each map and probably it would take a draftsman two weeks per map to post the data.

Other programs in use include the reduction of gravity data to datum and computation of seismic interval times, interval velocities, and average velocities from velocity profile data. Besides those programs others have been designed and used to solve non-recurring problems.

How electronic computers will be used in geophysics in the future will largely depend on our imagination and understanding of them. The electronic computer will not replace the geophysicist but will relieve him from much of the tedious calculations involved in geophysical work and will allow him more time to study the problem of where to find oil. That, after, all, is the problem our companies have employed us to solve.

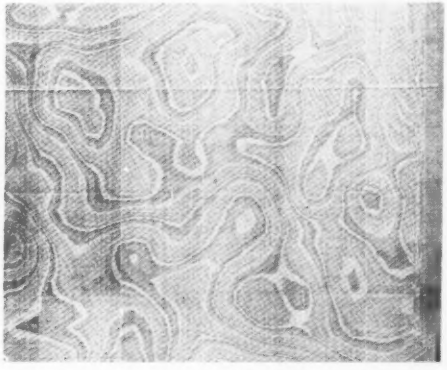

FIG. 11

GEOPHYSICS, VOL. XXVI, NO. 1 (FEBRUARY, 1961), PP. 45-56, 9 FIGS.

GRAVITY PROSPECTING FOR REEFS: EFFECTS OF SEDIMENTATION AND DIFFERENTIAL COMPACTION*

S. H. YUNGUL†

Abstract: The classical questions are: "Do reefs create recognizable gravity anomalies?" "If and when they do, then what causes these anomalies?" To find the answers to these questions, first a study of the case histories was made. It indicated that deeply buried, "isolated," organic reefs frequently create recognizable but "mysterious" gravity anomalies, and that there is no evident direct relation between the reef mass and the gravity anomaly. To find out the causes of these anomalies, the field of investigation proved to be so large that this paper could be entitled "a tentative density analysis of the sedimentary subsurface." The reef mechanism and the depositional processes are such that there is a concentration of sand in the over-reef section. Densities in clay and sand mixtures were investigated in terms of composition and depth of burial. The sand concentration alone is capable of creating shallow positive and deep negative density contrasts sufficient to account for the major part of the gravity anomaly. The gravity effect of a hypothetical reef was calculated. The result was very much like those actually observed. The gravity anomaly depends mainly on what has happened after the reef was buried, and not on the contrast at the reef level.

INTRODUCTION

The presently known major productive reef provinces in the world are almost all confined to North America. The development of reef exploration largely took place during the last fifteen years. This situation does not necessarily mean that reef growth favored North America. It also does not mean that effective surface exploration methods have been found. The main reason is simply that North America has been the scene of the most extensive "wildcat" drilling during the last fifteen years, and most of these reef fields have been discovered more or less by chance. It is very likely that the present day is merely the dawn of reef-oil history.

The reflection seismograph has made appreciable strides, but reef finding is still a highly uncertain problem. Gravity has been useful to some extent, but it has received too little research attention in the literature. Consequently, its outcome has been vague and controversial. Is gravity an economical tool in reef finding? The answer usually depends on the person's luck in the past. If it is an economical tool, then what kind of anomalies do reefs produce? Basically many different kinds. Can these anomalies be recognized and interpreted? They can sometimes be recognized, but, leaving interpretation aside, most of them have not so far been explained even on the basis of "known" geologic cross-sections, after the fields have been developed by drilling. One of the main reasons responsible for this confusion is the missing part of the "known" geology, namely the three-dimensional density data (lateral and downward).

The writer does not believe that gravity is or will be the best tool in finding reefs. But it has potential for providing some amount of reconnaissance or complementary detail information, and it deserves more consideration than it has received. To develop a satisfactory understanding of the problem, once in a while we have to put the old and new data in front of us and revise our thinking, make some more deductions, and speculate some more. This is what the writer aims to do in this paper.

In what follows, only the "true reefs" of the "isolated type" will be considered. The writer will avoid, as much as possible, unnecessary repetitions of the geological and paleoecological information that can be found elsewhere.

A reef complex is a rigid aggregate of rock,

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mainly calcareous, composed of the remains of colonial and solitary fauna and flora of the sea bottom, which is built upward at a more rapid rate than the terrigenous sediments deposited about its margins, in defiance of the action of waves and currents. The result is a relatively rigid framework in the form of a mount or ridge, or an irregular mass, which presents considerable vertical prominence with steeply sloping margins. The reef, as defined in this paper, includes the central rigid core, and most of the reef-derived detritus around it.

As far as the oil potentialities are concerned, the "isolated" type of reef is the most important. In what follows we shall confine ourselves to the isolated type, not only because this type has been proven to be the most important oil producer, but also because it lends itself to gravity prospecting in a less complicated way than the other reef types. A typical isolated reef is formed on shallow, submerged bottom. Enclosing sediments are generally uniform on all sides, with no appreciable back-reef facies immediately adjacent to the reef. This is a specific but not necessarily rare type. A reef archipelago is a group of isolated reefs. An atoll is a closed archipelago.

CASE HISTORIES

An extensive literature survey of the geophysical and geological case histories was done. It included the following reef gravity surveys in the three major productive provinces:

1. West Texas: North Snyder, Wilkirson, Sharon Ridge Canyon, Jameson, Good, Eskota.

2. The Great Lakes Region: Dawn 47–49, Dawn 59–85, Dawn 156, Weaver.

3. Alberta: Leduc, Wizard Lake, Bonnie Glen, Glen Park, Westrose, Erskine.

The data are too voluminous to present here. However, a summary of the case histories is shown in Table I.

The results of this literature survey can be summarized as follows:

1. Reefs frequently show recognizable gravity anomalies which may be (a) a simple high, (b) a high with a negative rim around it, (c) a low with a positive tendency in the center, or (d) a simple low. Most frequently it is a high with a negative rim around it, like a "sombrero."

2. When the anomaly is of the sombrero type or a simple high, its intensity is of the order of +0.5 mg. This is greater than an allowable density contrast between the reef mass and the enclosing sediments could produce. What is more, a gravity high may be present even when the reef density is less than that of the enclosing sediments. Clayton (1951) reports that at North Snyder the cores show the reef is less dense than the surrounding shales. Yet the anomaly is +0.6 mg.

3. The existence of a negative rim has so far not been satisfactorily explained.

4. The gravity highs are too narrow to be generated by masses at specified reef depths.

5. When the anomaly is of the sombrero type,

TABLE I. REEF GRAVITY, AVERAGE CONDITIONS AND RESULTS IN THE THREE REGIONS

GEOGRAPHY	GEOLOGY							GRAVITY			
REGION	DEPTH TO REEF BOTTOM (FEET)	HEIGHT OF REEF (FEET)	WIDTH OF REEF (MILES)	REEF ROCK	ENVELOPE FORMATION	DRAPING	BASAL STRUCTURE	REGIONAL	RESIDUAL		
									mg	mg	ZERO WIDTH (MILES)
WEST TEXAS (MIDLAND BASIN)	7000	600	2.5	$CaCO_3$	SANDY SHALE	YES	LOCAL HIGH OVER A REGIONAL HIGH	FLANK, NEAR APEX OF A HIGH, 3mg/MILE		+0.6	2.5
THE GREAT LAKES REGION	2000	300	1.2	?	DOLOMITIC BEDS, AND SALT BEDS THINNING OR WEDGING OVER REEF	WITH SALT LAYER: NO. WITHOUT SALT LAYER: YES.	?	?		+0.4	1.2
ALBERTA	6000	500	1.0	DOLOMITE	CALCAREOUS SHALE	YES	?	FLANK	+0.25		1.5

the width of the positive is of the order of the width of the reef, irrespective of the reef depth.

6. The local (residual) anomalies are frequently located near the apexes of regional gravity highs.

7. As far as West Texas is concerned, the reef bottoms are local positive reliefs. We have no such data for the other regions.

8. Thinning and draping in the shales over and around the reefs are more than that indicated by conventional calculations of differential compaction.

9. Pohly (1953) reports that the dips shown for the beds above the reefs on seismic maps are often greater than those encountered in drilling. This may be considered as indirect evidence of a lateral increase in density over reefs, because a velocity increase is usually accompanied by a density increase.

10. Either because of certain underlying causes, or merely because of world-wide abundance of shales, the surrounding regional formations are shales in most cases.

11. The equivalent porosities in the reefs are estimated to be of the order of 12 percent. The main constituent of most reefs is calcium carbonate. Consequently, the density is about 2.5.

12. The reef heights are from about one hundred to about eight hundred feet, widths $\frac{1}{2}$ to 3 miles, and the known depths 2,000 to 7,000 ft. The slopes on the flanks may be up to 40 degrees.

13. In view of the wide ranges of the observed reef geometries and anomaly types, it seems, at present, that there is no direct, evident relation between the reef mass specifications (depth, height, extent, density) and the gravity anomaly specifications (type, intensity, extent). Consequently, certain factors other than the reef mass play the major role.

GEOLOGICAL CONSIDERATIONS

The purpose of this section is to investigate the density distribution alone. However, the anomalous density distributions which are responsible for the reef gravity anomalies are closely related to the entire geologic history of the basin. One is forced to investigate, at least, the mechanism of the "reef ensemble" and its consequences in terms of structure and sedimentation.

Isolated reefs were started in widely extending seas, on shallow submerged bottoms (less than about 25 fathoms for modern reefs). This observation alone suggests that the reefs were rooted on broad, regional positive reliefs or near the slope breaks of shelves. Thus, reef gravity anomalies are expected frequently to be associated with broad gravity highs, as indicated by the case histories.

Reefs seem to have no preference as to the bottom rocks, with the exception that they do not root on loose sand. Most frequently they are rooted on unconsolidated clay and calcareous muds. The deposition around the reef has to be much slower than the reef growth, because reefs can tolerate only a small volume of settling mud. Geologically speaking, the reef growth may be considered as very rapid. At the end of the growth the thickness of the surrounding sediments must be small compared with the reef thickness. This is to say, the reef is formed as though a large, rigid mass were located on the unconsolidated sediments of the sea bottom. Referring to Figure 1, let us assume that a 500-foot-high reef having a density of 2.41 is laid on the fresh depositional surface of a 1,000-foot-thick basal shale resting on a rigid basement, and find out what the differential compaction processes will be. The calculations will not be shown here due to the limitations in space, but the results are shown in Figure 1. At the end of the reef growth (Figure 1A), the reef mass has sunk into the shale by 90 ft.

Let us assume that further shale deposition starts after the reef growth has ceased, and that no concurrent deposition takes place over the reef top. By the time the depositional surface is even with the reef top, we find that the off-reef basal shale has shrunk to 935 ft. Thus the reef bottom is now 25 ft lower than the top of the basal shale (Figure 1B). Referring to Figure 1C, let us suppose still further deposition, both over and off the reef. Differential compaction continues, such that when the basal shale is at a depth of 4,650 ft, the reef bottom is even with the top of the basal shale. A marker that was laid horizontally, as in Figure 1B, has developed an extra closure of 25 ft. If the reef top and the basal shale top had been one rigid surface all the time, the closure on the marker would have been 135 ft, and now it is 160 ft. In case of further burial beyond the 4,650-ft depth, the reef bottom becomes higher than the basal shale top. This process is equivalent to that in which the reef is uplifted like a salt

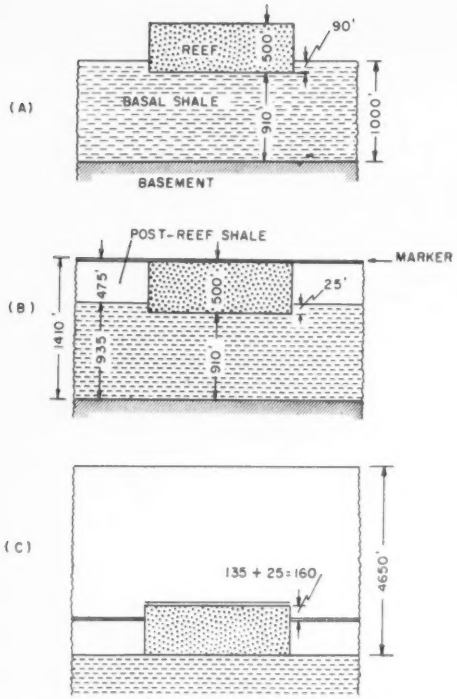

FIG. 1. Differential compaction at the reef bottom, and its effects on draping.

dome. And this relative upward movement continues as more sediments are deposited. The figures obtained above are somewhat conservative. The denser and thicker the reef, and the thicker the basal shale, the more pronounced the relative upward movement.

What has been said above is substantiated by field observations. Known geologic sections show the excessive draping and thinning. Intricate fracturing observed in all parts of reefs may be caused by the aforementioned differential vertical movements. Faulting is observed in the pre-reef layers. Settling of the reef into the bottom and intricate deformation structures in the marginal beds are observed in outcropping small fossil reefs. Dips as steep as 30 degrees have been reported in limestones which lap against the reef flanks.

The consequence of the mechanism described above is that a reef maintains a submarine topography for the entire duration of the sedimentation; the relief of this topography does not die off, upwards in the sedimentary column, as early as that due to a common "buried hill." It is, more or less, a plateau type bottom topography which can appreciably affect the sedimentation especially when the water is shallow. The sediments deposited over the summit are thus subject to greater agitation of water than those in the surroundings. The finer sediments are carried away from the reef, so that in the over-reef column there is a concentration of coarser material (sand). The bottom topography is reduced as the deposition progresses, so does the lateral difference in the sediments. We do not have any quantitative data as to the sand distribution. However, regionally anomalous lenticular sand bodies right over reefs or over their slope breaks are common. Silt and sand concentrations over structures associated with common "buried hills" are observed in the Gulf Coast and elsewhere.

It will be shown in the following section that a sand distribution of this kind can create appreciable amounts of negative density contrasts in the layers near the reef top and positive contrasts in the shallower layers, and that it may be responsible for the major part of the observed gravity anomalies.

DENSITIES

Let us consider, first, the regional densities, as if they were not influenced by any diastrophism and by the presence of a reef, and then bring out the contrast between the over-reef and the off-reef sections. We shall assume that mechanical compaction has reached the equilibrium condition, and that the reversible part is negligible.

Regional Densities

Shales.—The geologic column is expected to include a large portion of shales, because about 80 percent of all the sedimentary rock in the world is shale. What is more, the envelope formations are shales in the majority of the known cases. Consequently, the subject of densities in shales is of major importance. We shall consider shale as made of clay with an insignificant amount of grains (sand).

It is well known that the mineral density of shales of different ages, localities, and depths display small variations of the order of ± 0.05, and the average is close to 2.65. On this basis, the natural density (pore space filled with water of

density 1.04) is

$$\sigma = 2.65 - 1.61\,P, \tag{1}$$

where P is porosity. It is also well known that the porosity is practically a function of gravitational compaction alone, and that it can satisfactorily be expressed in terms of maximum depth of burial alone.

The writer believes that H. D. Hedberg's (1936) paper supplies the most reliable and complete results so far published. Curve "a" of Figure 2 is constructed on the basis of his actual porosity measurements and on equation (1).

Sands.—Next let us consider a sandstone or sand which contains no clay. Its grains are larger than silt size.

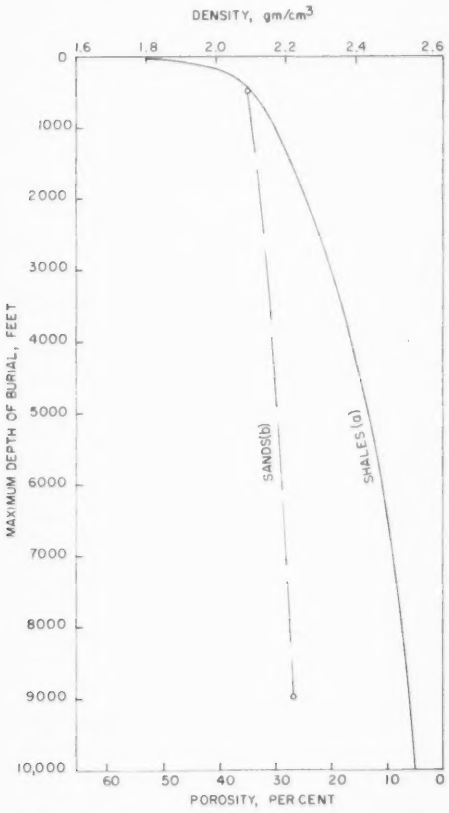

FIG. 2. Density and porosity as functions of depth of burial in shales and sands. (Curve for shales is based on data published by Hedberg, 1936.)

It is generally accepted that equation (1) is valid for all the rocks commonly occurring in sedimentary basins (clay, sand, lime). Then the porosity is always the governing factor. However, the porosity in sands cannot generally be predicted from the depth of burial alone, mainly because it depends largely on the degree of cementation.

Under normal conditions, that is, in the absence of unusual cementation conditions, the porosity can be expressed, in a crude way, in terms of the maximum depth of burial alone, inasmuch as the burial depth governs the ultimate pressure and temperature.

Data in the literature indicate that porosity of sands at a depth of five hundred feet is about 0.35. Core samples from Louisiana[1] indicated that the porosity at about 9,000 ft depth is about 0.27 (the data are shown by circles in Figure 4). This figure can be classified as that under normal conditions, because the samples contain less than one percent carbonate, and because the case represents little more than gravitational compaction. Converting the two values of porosity into densities by equation (1), and interpolating (guessing) in between, we obtain the density vs. depth relation, curve "b" of Figure 2. It is understood that there can be no generalized curve. This function, at best, must be represented by a band of which the lower boundary would indicate the minimum possible densities at various depths. Curve "b" of Figure 2 can be considered as one which is close to this lower boundary, with anticipated erratic density increases up to about 0.2.

Clay and Sand Mixtures.—The problem becomes more complicated when we turn to shaly sands and sandy shales with varying sand-to-clay ratios. The object is to construct a family of curves, or a surface, showing the $\sigma(S, D)$ function, where σ is density, S is the ratio of void-free sand volume to void-free total volume, and D is the depth of maximum burial. We have seen above that, for sands and clays, the porosity, P, is related to density via equation (1). We shall determine the $P(S, D)$ function first, and then convert it into $\sigma(S, D)$ by means of equation (1).

It is understood that depth of burial and sand percentage are not the only factors, and that the

[1] L. C. Bonham and D. Davis, personal communication.

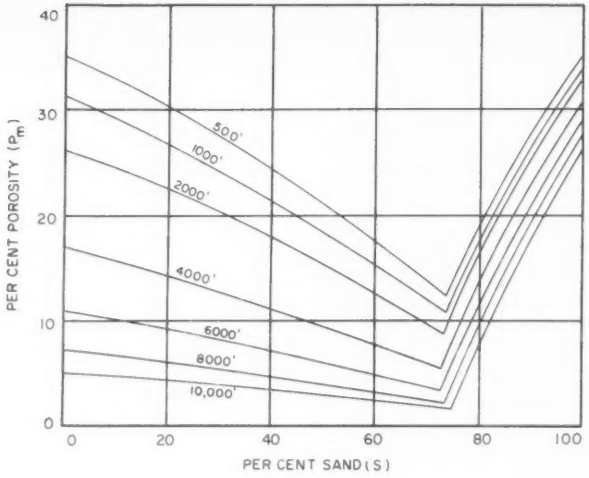

FIG. 3. Theoretical porosities in sand-clay mixtures as functions of composition and depth of burial. Each curve is related to the depth that is indicated on it, in feet.

porosity function is different for every locality, even for identical original constituents. Here it is not our intention to come out with exact relations for certain basins. We simply want to know the general behavior and order of magnitude of density variations, so that we can form a line of thinking for gravity prospecting problems.

The curves "a" and "b" of Figure 2 supply the $\sigma(S, D)$ functions for the two limiting values of S, zero and one hundred. Let us assume that the sand grains in clay are merely replacing an equal volume of porous clay. In other words, all the voids between the sand grains are fully packed with clay which behaves according to curve "a." This reasoning requires that the ratio of sand grain diameter to clay particle diameter be very large. Then, up to a certain critical composition, the porosity of the mixture is

$$P_m = \frac{1 - S}{1 - SP_c} P_c, \tag{2}$$

where P_c is the clay porosity (decimal value). Equation (2) is valid for the range in which the value of P_m varies from P_c to P_cP_s, where P_s is the porosity of 100 percent sand. The sand ratio for $P_m = P_cP_s$, minimum possible porosity, is

$$S_0 = \frac{1 - P_s}{1 - P_cP_s}. \tag{3}$$

For sand ratios higher than S_0, the pore spaces of sand cannot be fully packed by clay, and the porosity of the mixture is

$$P_m = \frac{P_s + S - 1}{S}. \tag{4}$$

These equations are plotted for different depths in Figure 3.[2]

In Figure 4, the circles are the data from Rapides Parish, Louisiana, from a depth range of 8,202 to 10,277 ft.[3] An approximate average of these circles is shown by the dashed line. The dot-dash line is the average of the same kind of data obtained by smoothing out the results for depths of 9,000 to 9,500 ft of Tensleep sandstones of Wyoming.[3] On Figure 4 are also shown three curves of Figure 3 to compare the actual data with the theoretical curves. The deviation between the two kinds is quite large, but it is expected. The closeness between the Louisiana and Wyoming curves is quite encouraging. For the reasons mentioned above, we shall assume that the Louisiana curve is a true representative of gravitational compaction. It is reasonable to expect that mixtures containing a small percentage

[2] The writer learned afterwards that a similar set of curves was constructed by Mr. A. E. Halteman (unpublished).

[3] L. C. Bonham, personal communication.

of sand should conform, more or less, to the full packing condition; the field data should follow the theoretical curves up to about 30 percent sand. The dashed line of Figure 4 is a compromise, for 9,000-ft depth, between the theoretical and actual values. Then the 500-ft depth curve has to be something like the dotted line. The curves shown in Figure 5 are drawn by interpolation.

According to Figure 5, at any depth of burial (down to 10,000 ft), there is a certain sand percentage that yields the maximum density. For higher sand percentages the density decreases rapidly.

Limestones.—There is no usable density vs. depth function for limestones at present. Actual densities in the majority of cases are between 2.5 and 2.7. The mineral density (calcite) is 2.70. In this paper we shall assume a density of 2.6 for common limestones.

Dolomites.—According to the published data, the natural density varies between 2.10 and 2.90, and it is about 2.80 for a typical dolomite. The mineral density is about 2.93.

Local Densities and Contrasts

Reef Mass.—Different parts of a reef may have widely differing porosities. The porosity may range, within a reef, from a few percent up to 30 percent. Very few data on average values are available. The only detailed study known to the writer was done in Scurry and Kent Counties of West Texas (Stafford, 1955). In this region the reefs are almost pure $CaCO_3$, with two percent insolubles on the average. The average effective porosity is 6 percent. Only an insignificant amount of it is of primary origin. Air permeability averages 4 millidarcys. These data indicate that the total (equivalent) porosity must be considerably higher, of the order of 10 to 15 percent.

In the Leduc-Woodbend area, Alberta, the porosity is difficult to determine from the cores. The Alberta Oil and Natural Gas Conservation Board uses 10 to 13 percent effective porosity for the producing zones.

We can conclude that the average total porosity is around 12 percent. On this basis, the density of a $CaCO_3$ reef is 2.50, and that of a dolomite reef is 2.70.

According to Figure 2, the contrast between $CaCO_3$ reef surrounded by shale may be anything between $+0.3$ and -0.1. For a dolomite reef the corresponding figures are about $+0.5$ and $+0.1$. Thus, the extreme values must be about $+0.5$ and -0.1.

Over-Reef Section.—Let us suppose that the off-reef sediments are all uniform shale containing 5 percent sand, and that the sand percentage varies in the over-reef section as shown in Figure 6A. On

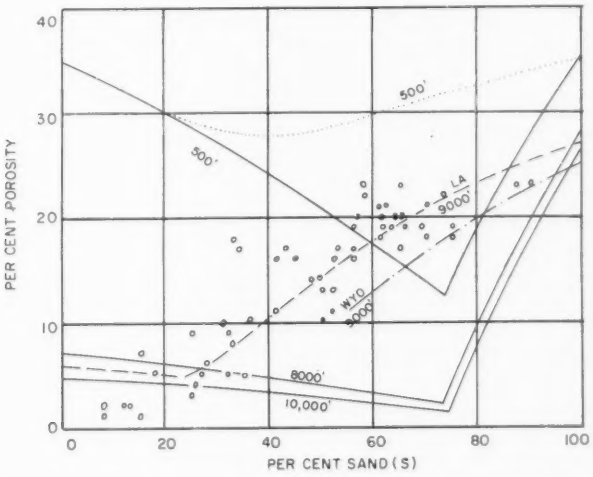

FIG. 4. Measured porosities in sand-clay mixtures as functions of composition and depth of burial. Dashed line (based on circles): Louisiana data; dash-dot line: Wyoming data; dotted line: speculative. (Solid lines are the theoretical curves of Figure 3.)

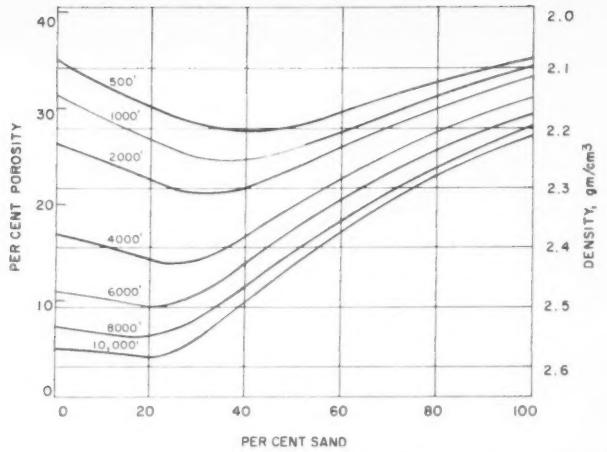

FIG. 5. Densities and porosities in sand-clay mixtures as functions of composition and depth of burial; a compromise between theory and actual measurements; based on Figures 3 and 4.

the basis of Figure 5, a density vs. depth curve is constructed for the off-reef section (Figure 6B, curve 1), and another one for the over-reef section (curve 2 of same figure). The density contrast between the off- and over-reef sections is shown in Figure 6C.

GRAVITY ANOMALIES

The foregoing sections provide explanations for the strange features of reef anomalies that were itemized in CASE HISTORIES. To crystallize the geologic concepts, we shall convert them into geophysical figures; this will be done by constructing a hypothetical reef, and finding the gravity anomaly due to each component.

The Hypothetical Reef

Our hypothetical reef is a circular "pinnacle" type. Figure 7A is a geologic cross-section (along a radius) that also shows the history of deposition

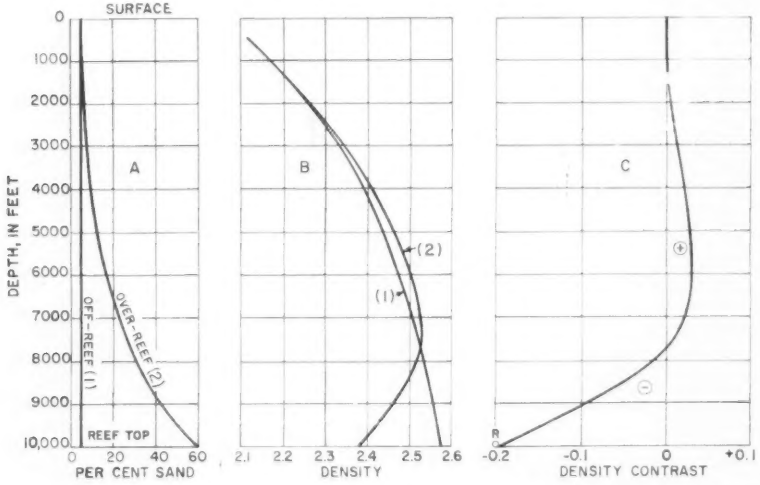

FIG. 6. Densities in the over- and off-reef sections, and the density contrasts, for assumed sand distributions in the shales over and off the reef, from the surface down to the reef-top level.

and erosion. This reef is similar to those in the Midland Basin and in Alberta. The closures were calculated first on the basis of differential compaction alone, and then altered, in accordance with the case histories, to account for extra draping and thinning. The bottom is flat. Figure 7B is the corresponding simplified geologic section. The purpose of the simplification was merely to facilitate the gravity calculations. The reef mass and the closures above it were reduced to horizontal circular discs. The actual volumes were assumed to be the averages of cones and cylinders of the same bases and heights.

Figure 7C shows the assumed sand (grain) distribution in the off- and over-reef sections of the overburden.

Figure 8D shows the density vs. depth functions in the two sections. The procedure has already been explained above. The reef density is 2.50, and that of limestone 2.6. Figure 8E shows the density contrast.

The anomalous mass distribution is represented

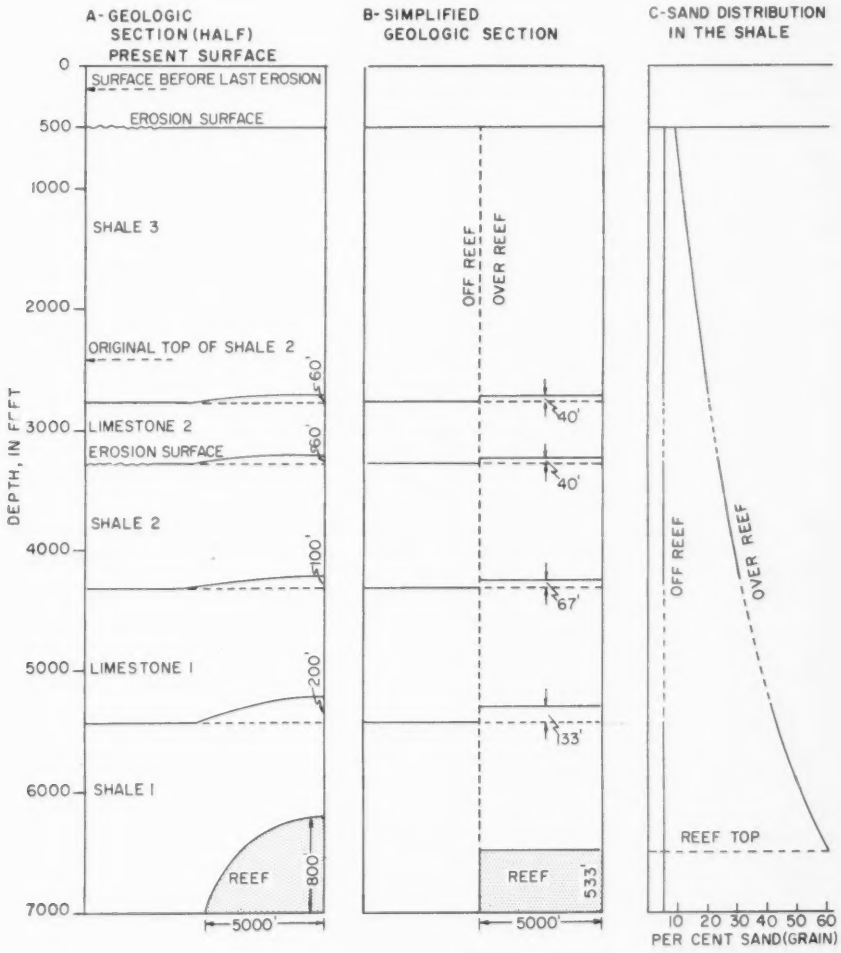

FIG. 7. The hypothetic reef. Structural and historical geology, and the assumed sand distribution. The reef is a circular "pinnacle" type, and the cross-section is along a radius.

by a pile of ten discs of different densities (contrasts); they form a vertical cylinder between the surface of the earth and the reef bottom, as shown in Figure 8F. Ten gravity anomalies, one for each disc, were calculated by making use of the published solid-angle graphs for horizontal circular discs.

The gravity calculation results are shown in Figure 9. The gravity effects are grouped into three components, namely those of the reef mass, the limestone layers, and the shale sections. The reef mass produces no anomaly. (This is not the result of a premeditated model, but a coincidence.) The total effect of the two limestone layers is a broad and weak negative (−0.015 mg) with a small positive in the center. The anomaly caused by the shale sections, which is due entirely to sand concentration, plays the major role (+0.4 mg central high and about −0.05 mg negative rim).

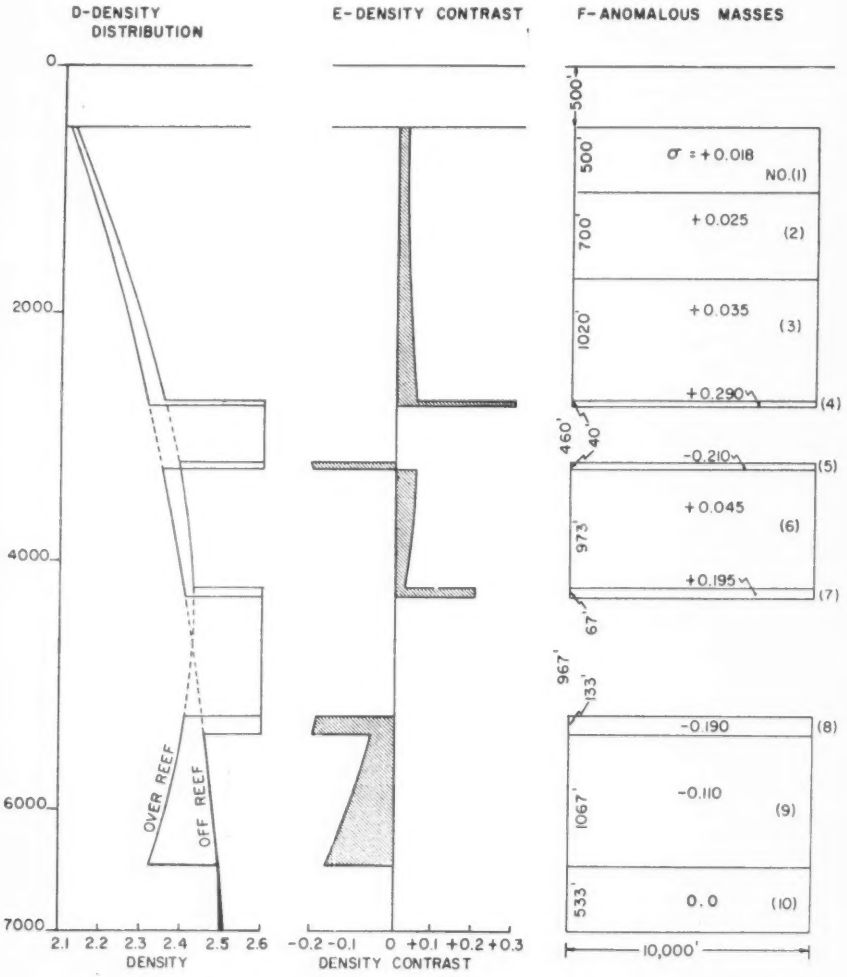

FIG. 8. The hypothetic reef. Densities, density contrasts, and anomalous masses based on the subsurface model of Figure 7.

The total anomaly, shown by the heavy curve in Figure 9, has the characteristics of the observed reef anomalies. Its form and intensity are much the same as those of an actual reef. The zero contour is close to the reef outline, just as is observed in the field. Obviously the width of the positive depends little on the reef depth. To sum it up, the outcome, which is in good agreement with the field observations, provides explanations for the peculiarities of reef anomalies itemized in CASE HISTORIES.

INTERPRETATION OF FIELD DATA

It seems that the critical stage of gravity prospecting for reefs, at present, occurs before the process of geologic interpretation takes over. This is the stage of isolating the reef anomaly (residual or derivative) from the total gravity.

We have seen that the negative rim is a potential criterion for recognition of reef anomalies. Therefore, we should do our best to preserve it in the final residual with as little distortion as possible. Those who are familiar with gravity work will recognize that this is an extremely difficult problem because the rim anomaly is weak, the central positive has a confusing effect, and the reef anomalies are frequently located near the apexes of regional gravity highs. The methods which can promise the highest degree of fidelity are the graphical ones, the "smoothers' residuals" (Steenland, 1952). However, these methods are subject to the judgment of the worker, and fail when the nature of the regional is unfavorable.

The second type of methods of isolating local anomalies is based on numerical treatment of points in regular arrays, the "gridding" type (Steenland, 1952). The center-point-and-one-ring residuals, and the second vertical derivatives are of this type. As far as the reef anomalies are concerned, these methods normally yield misleading results for the following reasons:

1. Let us consider the anomaly of a horizontal disc-shaped excess mass. It has no negative part, yet the "gridding" methods yield a negative rim-anomaly and a narrower central high. In other words, these methods have a tendency to make "reef anomalies" out of every simple high.

2. In practice, the role of the grid size is akin to that of a "band-pass" filter. If we set the filter to emphasize the central high, then the negative rim will loose its identity, and vice versa. However,

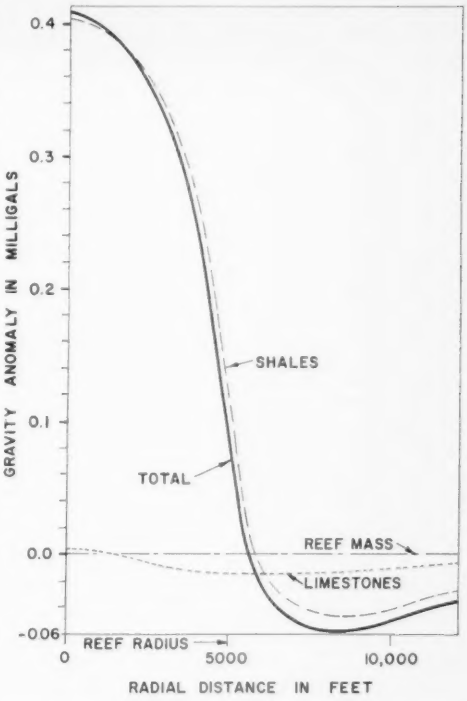

FIG. 9. Gravity anomaly due to the hypothetic reef.

in spite of its drawbacks, the "gridding" method may sometimes be practical in qualitatively isolating reef anomalies to serve as guides, if the negative rim is brought out by means of a grid of small size, say 2,000-ft radius, in addition to the customary residual map obtained by a relatively large size grid. The small-grid map will be more reliable than the customary map in indicating the reef criterion (the true negative-rim); it will also approximately determine the width of the reef (width of the central positive). However, these "residuals" cannot be used for quantitative interpretation.

Still another type of residual is that which is obtained by subtracting a "grid regional" (calculated by means of orthogonal polynomials for instance) from the total gravity. This type of residual seems to be comparable to the "smoothers' residuals"; it would indicate the reef criterion, and be acceptable for quantitative interpretation.

A somewhat quantitative interpretation can be

achieved, as one might expect, only by a trial-and-error method, by calculating the gravity effects of a number of carefully estimated "hypothetical" reefs. However, so long as the anomaly is mainly due to the grain distribution in the shales, one would be at a loss in assuming a realistic model.

CONCLUSIONS

True reefs of the isolated type frequently show recognizable gravity anomalies. Most frequently the anomaly is a positive, of the order of +0.5 mg, with a true negative rim around it; the zero anomaly contour is usually close to the reef outline.

Generally speaking, no evident direct relation between reef specifications and gravity anomaly specifications can be expected. The main contribution of the reef itself to the anomaly lies not in its mass at present but in its very unusual original condition which influences the geologic processes to come. The anomaly depends largely on what has happened after the reef was covered, and to some extent on the lithology of pre-reef formations. The major cause of the anomaly is probably the lateral variations of sand content in shales around and above it.

These conclusions are encouraging in that we have the reasons to expect recognizable anomalies even though the reef mass itself may not represent a density contrast. They are discouraging, on the other hand, because they indicate that the problem of quantitative interpretation of the gravity is to remain an uncertain task.

Regional surveys to locate the "belts" favorable to reef growth can be useful, but the potentiality of gravity surveys at present lies in precise, detailed surveys to locate the isolated reefs in a known reef region or belt.

Still another conclusion, although not related to reefs, is that one might expect appreciable gravity anomalies due to lithologic variations, such as where sandy shales grade into shaly sands.

ACKNOWLEDGMENT

The author wishes to thank F. G. Blake, L. C. Bonham, and G. A. Risley of the California Research Corporation for reading and criticizing the paper.

BIBLIOGRAPHY

The following chronologically arranged bibliography contains only the reef gravity literature. The geological and paleoecological literature is too numerous to be cited here. Some of the information shown in Table 1 was based on unpublished reports and personal communication.

Agnich, F. J., 1949, Geophysical exploration for limestone reefs: Geophysics, v. 14, p. 486–500.

Brown, Hart, 1949, A precision detail gravity survey, Jameson area, Coke County, Texas: Geophysics, v. 14, p. 535–542.

Klaus, H. and Hughes, J. C., 1951, Gravity exploration for reefs and other porosity maxima: World Oil, v. 132, no. 7, p. 78–84.

Pohly, R. A., 1954, Gravity case history: Dawn No. 156 pool, Ontario: Geophysics, v. 19, p. 95–103.

McCarver, H. C., 1954, Geophysical history of the Good field, Borden County, Texas: Geophysics, v. 19, p. 791–801.

Agnich, F. J., 1955, Exploration for reefs by geophysical methods: Proc. of the 4th World Petroleum Congress, Section I, p. 619–634.

Stackler, W. F., 1955, Structural prospecting with the gravity meter: Oil in Canada, v. 7, no. 39, p. 52–62.

Dyer, W. B., 1956, Gravity prospecting in southwestern Ontario: Canadian Oil and Gas Industries, v. 9, no. 3, p. 37–43.

Pohly, R. A., 1956, Reefs are hard to find: World Oil, v. 143, no. 1, p. 75–78.

Stone, R. C., 1956, Geophysical history of the Sharon Ridge Canyon field, Scurry County, Texas: Geoph. Case Histories, Society of Expl. Geoph., Tulsa, Oklahoma, v. II, p. 227–233.

Ralston, W. and Rettger, R. E., 1956, Case history of the Jameson Reef field, Coke County, Texas: Geoph. Case Histories, SEG, Tulsa, Oklahoma, v. II, p. 200–214.

REFERENCES

Clayton, Neal, 1951, Geology and geophysics of the N. Snyder area, Scurry County, Texas: Geophysics, v. 16, p. 1–13.

Hedberg, H. D., 1936, Gravitational compaction of clays and shales: Amer. Jour. of Science, v. 231, no. 184, p. 241–287.

Pohly, R. A., 1953, New gravity approach aids reef interpretation: World Oil, v. 136, no. 6, p. 116–124.

Stafford, P. T., 1955, Zonation of the late-Paleozoic Horseshoe atoll in Scurry and southern Kent Counties, Texas: USGS Oil and Gas Investigations, Chart OC 53.

Steenland, N. C., 1952, Review of "Regional correction of gravity data," by Raoul Vajk: Geophysics, v. 17, no. 2, p. 409.

GEOPHYSICS, VOL. XXVI, NO. 1 (FEBRUARY, 1961), PP. 57–76, 5 FIGS.

AN EVALUATION OF THE GRAVITY CONTROL NETWORK IN NORTH AMERICA*

J. C. BEHRENDT† AND G. P. WOOLLARD‡

Abstract: Observations with a LaCoste and Romberg geodetic gravimeter having a very low nearly linear drift rate, a high reading precision, and a world wide range were made at approximately three hundred sites in order to check and extend the gravity control network in North America. The sites occupied were mostly at former gravimeter bases located at airports, harbors, universities, and pendulum stations. The instrument was calibrated against the North American standardization range of pendulum measurements from Paso de Cortes, Mexico, to Fairbanks, Alaska, using the weighted mean values of the observations established with the U. S. Coast and Geodetic Survey, Cambridge University (England), and Gulf-University of Wisconsin pendulum equipment. A statistical evaluation of the precision of the network based on reoccupations at 40 major control stations gives an estimated standard deviation of 0.08 mgal. The airport network of bases previously reported by Woollard (1958) that was established with high range Worden gravity meters was found to require a systematic correction of 0.3 mgal per 1,000 mgal change because of the difference in calibration standard used. The adjusted values for the forty airport stations reoccupied agree on the average to 0.2 mgal with the results of this study. The reoccupations of the old pendulum observation sites of the U. S. Coast and Geodetic Survey suggest that much of this network is in error by over 3 mgals. Descriptions of sites occupied and the principal facts for position, elevation, observed gravity, and free-air and Bouguer anomalies are presented.

INTRODUCTION

The principal reason for the study here reported is that a new gravity map of the United States is being prepared and much of the available data is either on a floating datum or is based upon gravity control stations of questionable reliability. In order to effectively integrate all of this material an accurate re-check of as many gravity base stations as is possible is therefore desirable. Although Woollard (1958) presented results for an airport gravity control network in the United States, very few of the older gravity surveys have been adjusted to this network as yet. Furthermore it appeared the reliability of Woollard's values could be improved somewhat as this work had been done with Worden geodetic gravimeters and was not believed to have an accuracy greater than ± 0.3 mgal. Other factors that were considered in setting up the program were: (1) within the past two years the use of gravimeters on surface ships has been materially advanced and it is desirable to have base stations at harbors along the east and west coasts and the Great Lakes which can be used for control in future work of this type; (2) the number of universities and research institutions that are carrying out gravity surveys of various kinds in addition to those being made in connection with oil exploration are steadily increasing. It was, therefore, deemed desirable to include observations at as many of these places as was feasible.

With these objectives the program here reported was carried out during the period from March through September of 1959 and observations were made at three hundred gravity base sites in North America with LaCoste-Romberg geodetic meter No. 1. Figure 1 shows the locations of the observation points.

REMARKS ON INSTRUMENTATION

As indicated above Woollard's airport network of gravity control bases had been established with Worden geodetic gravimeters and although this instrument prossesses the virtues of portability, temperature compensation and a high range, it suffers from a varying drift rate, frequent tares, occasional temperature shock, and is difficult to calibrate adequately for a precision greater than

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FIG. 1. Location of observation sites used in evaluation survey.

0.2 mgal. With the development of the high range, high precision, low drift LaCoste-Romberg geodetic gravimeter it was felt that an evaluation of gravity base stations in the United States to an accuracy of one-tenth of a milligal was obtainable.

This instrument although it requires an external power supply and must be maintained at constant temperature and is not as portable as the Worden meter, does have a very low, nearly constant linear drift rate, few tares, a 6,000 milligal range without resetting and a reading sensitivity of ± 5 microgals. For any study in which precision is the first requisite, the advantages of the LaCoste-Romberg instrument far outweigh its disadvantages.

PREVIOUS EVALUATIONS OF GRAVITY CONTROL IN THE UNITED STATES

Many gravity surveys in the past have been based upon the values of gravity at the thousand-odd pendulum stations established by the U. S. Coast and Geodetic Survey (Duerksen, 1949) throughout the United States. Previous evaluations of these bases by Ferris (1943) and Woollard et al. (1955) showed that some of these stations values are in error by 10 mgals or more and many

TABLE I. RESULTS ON NORTH AMERICAN STANDARDIZATION RANGE

		Gravimeter Determinations	Estimated Standard Error	n	Weighted Mean of Pendulum Determinations	Estimated Standard Error	n
GW 3	Madison, Wis.	980.3689 gals base assumed			.3689 gals	.06 mgl	13
GW 105	Pt. Barrow, Alaska	982.6997	0.08* mgl	1	.6998	.32	3
GW 27	Fairbanks (Ladd), Alaska	982.2444	0.05	2	.2445	.22	6
GW 26	Whitehorse, Canada	981.7486	0.08*	1	.7493	.28	7
GW 29	Fort St. John, Can.	981.4059	0.08*	1	.4063	.34	5
GW 25	Edmonton, Can.	981.1678	0.02	5	.1681	.24	12
GW 32	Calgary, Can.	980.8281	0.08*	1	.8283	.36	3
GW 34	Cut Bank, Mont.	980.6085	0.08*	1	.6083	.46	2
GW 4	Great Falls, Mont.	980.5270	0.05	2	.5265	.25	7
GW 35	Billings, Mont.	980.3710	0.05	2	.3707	.36	3
GW 52	Beloit, Kan.	979.9978	0.05	2	.9981	.23	8
GW 51	Tulsa, Okla.	979.7663	0.05	4	.7655	.24	5
GW 18	Houston, Texas	979.2983	0.10	2	.2982	.20	9
GW 21	Monterrey, Mex.	978.8055		3	.8052	.27	7
GW 19	Mexico City (Tac), Mex.	977.9419	0.01	3	.9421	.19	7
GW 42	Paso de Cortes, Mex.	977.5711	0.08*	1	.5712	.38	2
	Other Pendulum Stations Established with Gulf-Wisconsin Pendulums						
U 337	Washington, D. C. Comm. vault on floor	980.1188	0.08*	1	.1187	.00	12
GW 2	Washington, D. C. Carnegie Institute	980.1006	0.00	2	.1006	.03	12
GW 1	Lamont Geological Observatory	980.2596	0.08*	1	.2593	.06	5

n = number of observations.
* Estimated standard deviation.

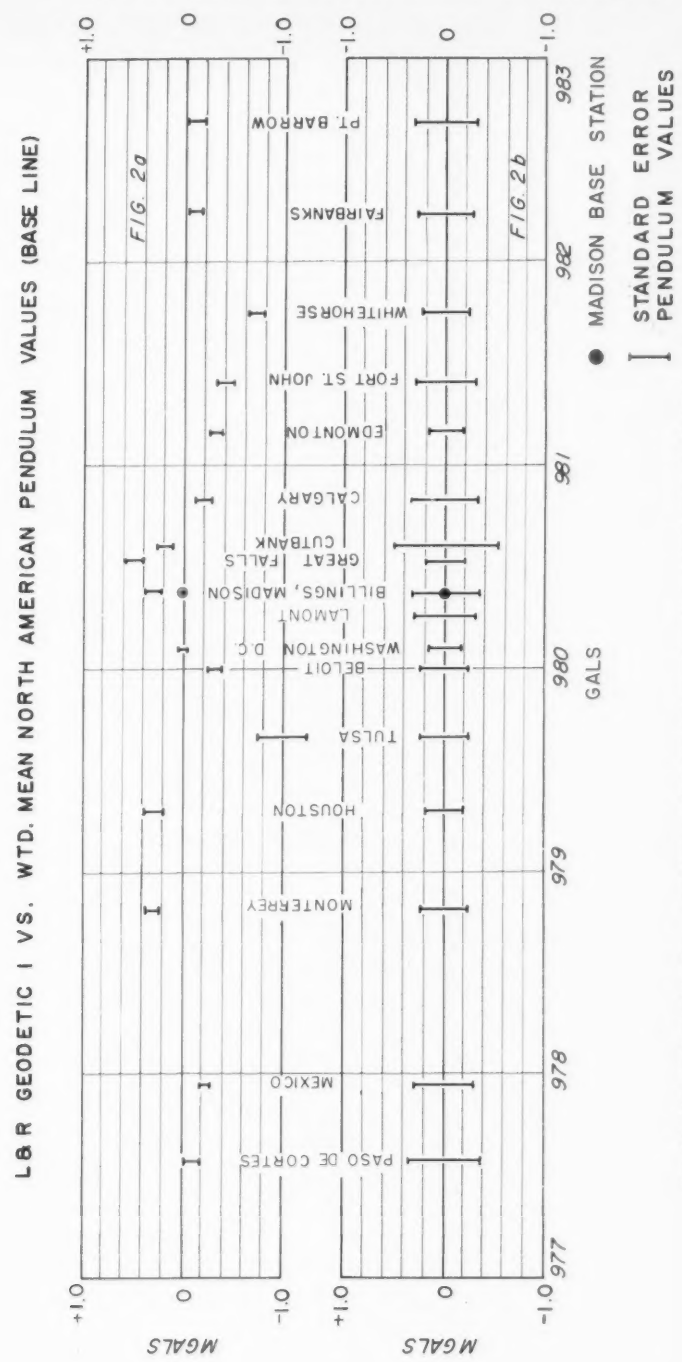

FIG. 2A. Comparison of LaCoste-Romberg geodetic meter 1 results with weighted mean Gulf-Wisconsin pendulum values.
FIG. 2B. Standard error of Gulf-Wisconsin pendulum values.

as much as three to four milligals. Therefore, one purpose of the present study was to spot check this gravity control network. Although a systematic re-check of the entire network is being made by the U. S. Coast and Geodetic Survey, this will require several years to complete.

The other gravity control network already referred to, is that established by Woollard (1958) at the airports throughout the United States. Although these stations are believed to have a reliability greater than 0.5 mgal it was felt desirable to both spot check these stations and to expand this network with the more accurate LaCoste-Romberg gravimeter.

STANDARDIZATION OF GRAVIMETER USED

The calibration of LaCoste-Romberg geodetic meter No. 1, was established by reoccupying key pendulum stations on the North American gravity standardization range of pendulum measurements between Paso de Cortes, Mexico, and Fairbanks, Alaska (Woollard, Rose and Bonini, 1956). Observations were made on a repeat basis on a closed loop. The gravity values used for these standardization stations are based upon the weighted means of the observations made with the U. S. Coast and Geodetic Survey, Cambridge University (England) and Gulf-University of Wisconsin sets of pendulum apparatus (Rose and Woollard in preparation for publication). Although any one set of observations made by the various groups could be the most accurate, the use of the weighted mean values for all three groups is the least subjective approach in establishing the value for these bases. As the response curve of the LaCoste-Romberg instrument had been determined in the laboratory by the manufacturer the observations could be fitted to the pendulum values as a linear function.

Table I (see Appendix) is a comparison between the gravimeter and the pendulum results for the stations occupied. This table also shows the estimated standard errors and number of observations in each case. Figure 2A is a plot of the difference in gravimeter and pendulum values. Zero ordinate defines the calibration factor that gives the best fit and is based upon a least square adjustment between the gravimeter values and the weighted means of the pendulum results. Figure 2B shows the uncertainty in the pendulum values. As is

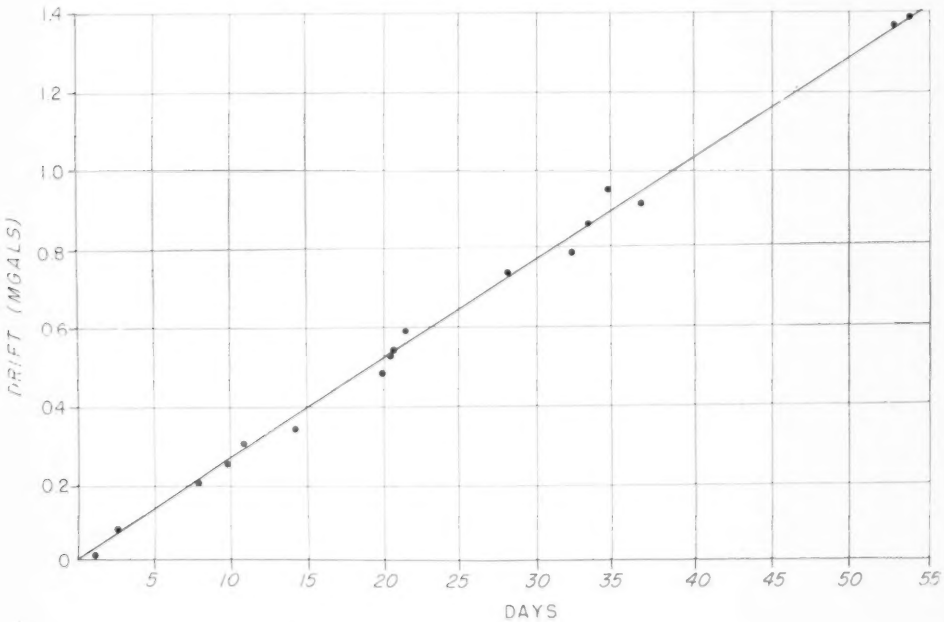

FIG. 3. Drift curve for LaCoste-Romberg geodetic meter 1.

TABLE II. GRAVITY RESULTS AT MAIN CONTROL STATIONS

	Location	$\bar{G}$	n	Estimated Standard Error
WA 279	Fairbanks AP	982.2464 gal	5	0.06 mgl
GW 27	Fairbanks PS	982.2444	2	0.05
WA 181	Edmonton AP	981.1729	5	0.05
WA 169	Port Angeles AP	980.8640	2	0.05
U 221	Everett PS	980.7807	5	0.00
WA 170	Seattle AP	980.7765	6	0.00
WA 124	Great Falls AP	980.5137	3	0.01
GW 4	Great Falls PS	980.5270	2	0.05
GW 35	Billings PS	980.3710	2	0.05
GW 3	Madison PS	980.3689	Base station	
U 30	Cambridge PS	980.4011	2	0.00
WA 113	AFCRC (Bedford)	980.3942	2	0.00
WU 20	New York (Col. U.)	980.2689	2	0.00
WA 132	New York (LaGuardia)	980.2825	2	0.00
WA 101	Chicago (Midway)	980.2864	9	0.01
U 36	Chicago (U.C.)	980.2858	2	0.05
WA 8	Washington, D. C. AP	980.1088	2	0.00
WA 145	Pittsburgh AP	980.0993	3	0.00
GW 52	Beloit, Kansas PS	979.9978	2	0.05
WA 120	Kansas City, Mo., AP	979.9998	2	0.05
WA 139	Tulsa AP	979.7766	2	0.05
GW 51	Tulsa PS	979.7663	4	0.05
WA 86	San Francisco AP	979.9883	2	0.05
WA 163	Salt Lake City AP	979.8070	2	0.00
WU 31	Blacksburg VPI	979.7324	2	0.00
WA 150	Knoxville AP	979.7032	2	0.10
WA 149	Chattanooga AP	979.6505	2	0.00
WA 177	Casper AP	979.9562	2	0.05
WU 7	Golden CSM	979.5842	2	0.05
WA 156	Ft. Worth AP	979.4934	4	0.05
WA 97	Atlanta AP	979.5205	3	0.00
WA 154	Dallas AP	979.5131	5	0.04
WU 39	Austin L&R	979.2849	2	0.00
WA 151	Austin AP	979.2889	2	0.00
WA 89	Denver AP	979.6335	4	0.01
WA 161	San Antonio AP	979.1973	2	0.05
GW 18	Houston PS	979.2983	2	0.05
WA 159	Houston AP	979.2932	2	0.00
WA 190	Monterrey AP	978.8617	3	0.06
WA 189	Mexico City AP	977.9701	2	0.00
GW 19	Mexico City (Tac)	977.9419	3	0.01

$\bar{G}$ Mean value corrected for earth tide.
n Number of observations.

seen in Table I the value for Tulsa shows a discrepancy of 0.8 mgal whereas all of the rest of the stations agree to about 0.3 mgal. The discrepancy at Tulsa is probably related to the fact that an exact reoccupation of the pendulum observation site could not be effected with the gravimeter. The standard deviation for the gravimeter observations used in establishing the calibration factor for the meter is 0.08 mgal. The 95 percent confidence limits for any one of the stations based on 16 degrees of freedom is ± 0.14 mgal.

SURVEY AND REDUCTION PROCEDURE

For general control over the country a network of stations was established by air travel at forty sites. These bases served as control for stations occupied using ground transport and each was occupied from two to nine times. Earth tide corrections were made using the tables prepared by the European Association of Exploration Geophysicists. The correction for instrument drift after allowing for earth tide effects averaged about one-tenth of a milligal per week. Figure 3 shows a typical drift curve for one section of the trip. The values of gravity for each site were based upon the observed differences from the pendulum base station at the University of Wisconsin (980.3689 gals) based upon the ties made by Woollard (1948) to seven international gravity bases tied directly to Potsdam.

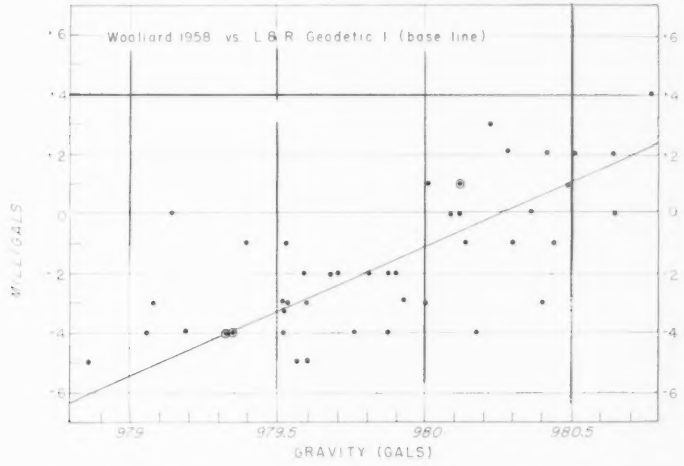

FIG. 4. Comparison of Woollard (1958) Worden meter values at airports with LaCoste-Romberg geodetic meter 1 results.

Table II (see Appendix) presents the results for the network of forty control stations. These were occupied on several different "trips" but owing to the high repeatability of the meter could be analyzed together statistically. The estimated standard deviation for the group is 0.08 mgals. The 95 percent confidence limits for any one of the stations in the control group is ± 0.13 mgals based on 14 degrees of freedom.

RESULTS OF PROGRAM

A breakdown on the observations in terms of locations is as follows:

111 Airport Stations
50 Universities and Institution Stations
61 Pendulum Stations
32 Harbor Stations (Great Lakes, Atlantic, Pacific, and Arctic Coasts)

Tables III through VI in the appendix give the station descriptions and observed gravity values for each of the above groups of stations. Tables VII and VIII present the principal facts, latitude, longitude, elevation, observed gravity, free-air anomaly and Bouguer anomaly for a density of 2.67 gm/cc for all sites where reliable location and elevation data are available.

COMPARISONS WITH PREVIOUS VALUES

In Table IX the values obtained on the present study are compared with those established at airports by Woollard (1958) using Worden gravimeters, and in Figure 4 the difference in values is plotted as a function of the absolute gravity value. As seen in Figure 4 the values appear to differ in a systematic manner with change in gravity indicating a difference in calibration standard. This can be accounted for by the fact that the calibration used by Woollard was based upon the preliminary values for the Gulf-University of Wisconsin pendulum results, only, on the North American standardization range. If Woollard's results are adjusted for the apparent difference in calibration of 0.35 mgal per 1,000 mgal change, the two sets of values are brought into substantial agreement. Except for two sites, Burlington, Vt., and Medford, Oregon, the two sets of data agree on the average to 0.2 mgal which is within the limit of ± 0.3 mgal originally claimed by Woollard. The discrepancy at Burlington, Vt., appears to have been a poor reading by Woollard, and at Medford, Ore., there is some question as to whether identical sites were used as the airport terminal had been rebuilt during the intervening period.

In Table X revised values and principal facts are given for all of the airport network bases originally reported by Woollard (1959) that were not reoccupied in the present study. This table and Tables III and VII are believed to provide reliable control on an absolute basis at airports throughout the United States and parts of Canada and Mexico.

COMPARISONS AT USC&GS PENDULUM STATIONS

In Table XI comparative values at the U. S. Coast and Geodetic stations occupied are listed

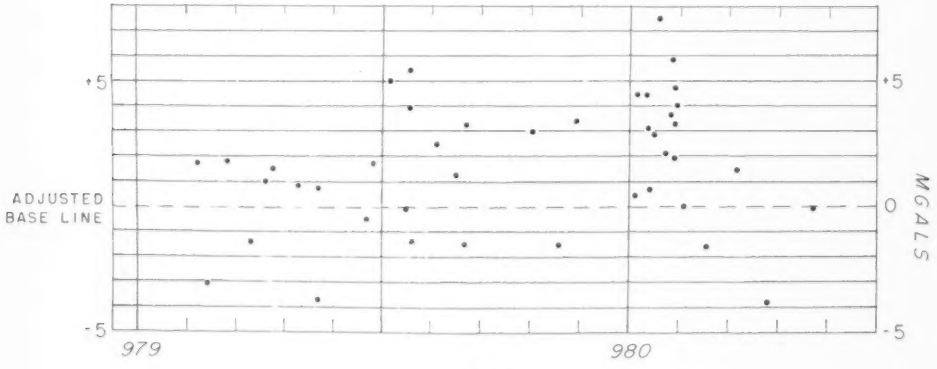

FIG. 5. Comparison of U. S. Coast and Geodetic Survey pendulum values with LaCoste-Romberg Geodetic meter 1 results adjusted to a common base.

TABLE III. L&R GEODETIC NO. 1 AIRPORT GRAVITY BASE STATIONS

Station		Station Description	Obs. Gravity
WA 81	Birmingham, Ala.	Barrier Gate 5.	979.5390
WA 82	Mobile, Ala.	Barrier Gate 2.	979.3396
WA 279	Fairbanks, Alaska	Lobby at E I beam.	982.2464
WA 280	Pt. Barrow, Alaska	In front of entrance to terminal.	982.6997
WA 281	Umiat, Alaska	On runway at edge of field.	982.5444
WA 83	Los Angeles, Calif.	United terminal at street exit in lobby, left of door.	979.5946
WA 84	Monterey, Calif.	Sidewalk curb in front of E front entrance to terminal.	979.8692
WA 85	San Diego, Calif.	Inside terminal lobby at middle door to street, at right side (facing out).	979.5369
WA 86	San Francisco, Calif.	Gate 23.	979.9883
WA 87	San Francisco, Calif.	Curb ground level, main entrance to terminal opposite 2nd pillar from south.	979.9885
WA 88	Santa Barbara, Calif.	At street curb in front of right hand arch to terminal facing terminal.	979.6407
WA 89	Denver, Colo.	Gate 2.	979.6335
WA 90	Denver, Colo.	Gate 6.	979.6327
WA 91	Kremling, Colo.	SW corner at hangar, at BM K297 USC&GS.	979.4903
WA 92	New Haven, Conn.	Exit to field at barrier.	980.3125
WA 93	Wilmington, Del.	On curb in front of east exit to street.	980.1757
WA 7	Washington, D. C.	Field level, field side of terminal, EAL air freight entrance, at Baggage Gate 6.	980.1098
WA 8	Washington, D. C.	Upper street level, northern doors, center on sidewalk.	980.1088
WA 94	Jacksonville, Fla.	Gate 6 and 7.	979.3856
WA 95	Pensacola, Fla.	Barrier, Gate 3.	979.3630
WA 96	Tallahassee, Fla.	End of left hand (facing field), concourse, under arcade.	979.3544
WA 97	Atlanta, Ga.	East concourse, Gate 1, (old terminal).	979.5205
WA 98	Atlanta, Ga.	West concourse, Gate 1, (old terminal).	979.5203
WA 99	Savannah, Ga.	Gate 2, field level.	979.4980
WA 100	Coeur d'Alene, Idaho	On concrete platform in front of street entrance to terminal lobby.	980.6387
WA 101	Chicago, Ill.	Midway, North Central Airlines terminal at water cooler.	980.2864
WA 102	Indianapolis, Ind.	Gate 5.	980.0933
WA 103	W. Lafayette, Ind.	Purdue Univ. Airport, terminal waiting room, in corner, opposite door to field.	980.1469
WA 104	Beloit, Kan.	In front of aluminum hangar at Phillips gas pump on concrete base of pump.	980.0000
WA 105	Kansas City, Kan.	At street entrance to terminal on side valk, next to steps.	980.0010
WA 106	Wichita, Kan.	Gate 3.	979.8404
WA 107	Lexington, Ky.	Gate 3.	979.8988
WA 108	Baton Rouge, La.	Gate 1.	979.3637
WA 109	New Orleans, La.	On sidewalk at curb in front of entrance to terminal.	979.3312
WA 110	New Orleans, La.	Moisant Airport, Gate 5 at barrier.	979.3298
WA 111	Portland, Me.	Inside terminal against N. wall E. of insurance machine.	980.5126
WA 112	Baltimore, Md.	Terminal street entrance, lower level, on curb against W. wall.	980.1104
WA 113	Bedford, Mass.	Hanscom Field, at Gate 2 to base, Bldg. 1101, outside door to Provost Marshall's Office, next to phone booth.	980.3942
WA 114	Boston, Mass.	Near Gate 17, in AA outbound baggage room.	980.4036
WA 115	Boston, Mass.	Gate 19.	980.4036
WA 116	Detroit, Mich.	Willow Run Airport, Gate 17, blue concourse.	980.3188
WA 117	Lansing, Mich.	Transient gate, field level (gate at NE corner of barrier).	980.3518
WA 118	Minneapolis, Minn.	Gate 1.	980.5950
WA 119	Meridian, Miss.	New terminal airport, by sewer at north end of barrier on field.	979.4840
WA 120	Kansas City, Mo.	Street entrance to terminal against building on sidewalk.	979.9998
WA 121	St. Louis, Mo.	Gate 17.	980.0043
GW 35	Billings, Mont.	West wall of Hangar No. 2, 7 ft N of door end. (Pend. Sta.)	980.3710
WA 122	Billings, Mont.	Barrier, Gate 6, new terminal.	980.3717
WA 123	Butte, Mont.	At barrier gate to terminal.	980.1744
WA 124	Great Falls, Mont.	Western Airlines desk in terminal.	980.5137
WA 125	Cut Bank, Mont.	Field door of customs inspection room.	980.6085
WA 126	Lewistown, Mont.	50 ft out on apron from barrier.	980.4510
WA 127	Missoula, Mont.	Inside terminal lobby at right of exit to field.	980.4440
WA 128	Las Vegas, Nev.	Center point in terminal lobby.	979.6049
WA 129	Reno, Nev.	N field entrance to U. S. Weather Bureau Building at foot of steps.	979.6873
WA 130	Albuquerque, N. M.	Barrier, Gate 2.	979.2081
WA 131	Santa Fe, N. M.	At right of terminal entrance from field.	979.1974
WA 132	New York, LaGuardia	Lower lobby at P.O. counter.	980.2825

(*Continued on next page*)

TABLE III. (*Continued*)

Station		Station Description	Obs. Gravity
WA 133	New York, Idlewild	Opposite entrance to customs in new terminal.	980.2261
WA 134	Syracuse, N. Y.	Barrier, Gate 2.	980.3968
WA 135	Cincinnati, Ohio	In front of terminal, 4 ft from N end of walk on flag circle, in road.	979.9935
WA 136	Cincinnati, Ohio	Gate 3.	979.9931
WA 137	Cleveland, Ohio	Gate 6 to field.	980.2322
WA 138	Columbus, Ohio	New terminal, Gate B1, field level.	980.0791
WA 139	Tulsa, Okla.	Gate 3.	979.7766
WA 140	Eugene, Ore.	Beneath marquee at terminal lobby entrance.	980.5148
WA 141	Medford, Ore.	Under marquee opposite Gate 3 at left of door.	980.2375
WA 142	Portland, Ore.	In lower lobby at right of doors to street at wall.	980.6483
WA 143	Portland, Ore.	Old terminal, under marquee at NE corner of curb.	980.6477
WA 144	Philadelphia, Pa.	Main entrance, at curb, opposite easternmost of doors.	980.1976
WA 145	Pittsburgh, Pa.	Gate 9.	980.0993
WA 146	Providence, R. I.	Gate 3 at barrier.	980.3139
WA 147	Charleston, S. C.	MATS terminal, processing room, against window wall, 2 ft from counter—same bldg. as U. S. Customs.	979.5674
WA 148	Charleston, S. C.	Municipal Airport at USC&GS BM, on porch field side of terminal.	979.5668
WA 149	Chattanooga, Tenn.	Street entrance to terminal on sidewalk at curb.	979.6505
WA 150	Knoxville, Tenn.	Gate 1 at southernmost barrier.	979.7032
WA 151	Austin, Texas	Next to terminal on concrete at Gate 1.	979.2889
WA 152	Brownsville, Texas	Barrier, Gate 1 (on concrete).	979.0509
WA 153	Corpus Christi, Texas	Barrier, Gate 2.	979.1430
WA 154	Dallas, Texas	Gate 11.	979.5131
WA 155	El Paso, Texas	Terminal lobby entrance at pillar beneath marquee.	979.0814
WA 156	Fort Worth, Texas	Gate 11, on sidewalk by sewer.	979.4934
WA 157	Galveston, Texas	Gate 2.	979.2696
WA 158	Houston, Texas	Gate 9, inside terminal.	979.2933
WA 159	Houston, Texas	Gate 7.	979.2932
WA 160	Laredo, Texas	Terminal street entrance, field level.	979.0792
WA 161	San Antonio, Texas	American Airlines street exit.	979.1973
WA 162	San Antonio, Texas	Gate 8.	979.1975
WA 163	Salt Lake City, Utah	Inside terminal at door to S concourse against E wall	979.8070
WA 164	Vernal, Utah	225 feet E of entrance to field and 90 ft S of section line rd, in open field.	979.6686
WA 165	Burlington, Vt.	Gate 2, barrier.	980.5181
WA 166	Norfolk, Va.	New terminal, street entrance to terminal on sidewalk at curb opposite center of main door.	979.8789
WA 167	Norfolk, Va.	Old station at eastern edge of 2 Piedmont hangars.	979.8788
WA 168	Roanoke, Va.	On sidewalk in front of terminal, NW end of walk at curb.	979.8076
WA 169	Port Angeles, Wash.	At 6 ft N of NE corner of base of control tower.	980.8640
WA 170	Seattle, Wash.	Gate 5.	980.7765
WA 171	Seattle, Wash.	Gate 3. Inside entrance against N wall.	980.7765
WA 172	Seattle, Wash.	At curb E end of walk from flag.	980.7765
WA 173	Spokane, Wash.	Terminal lobby in front of fireplace.	980.6463
WA 174	Charleston, W. Va.	Barrier, Gate 6.	979.9259
WA 175	Janesville-Beloit, Wis.	Rock County Airport at gate.	980.3303
WA 176	Milwaukee, Wis.	Gate 16, field level.	980.3597
WA 177	Casper, Wyo.	Gate 3.	979.9562
WA 178	Cheyenne, Wyo.	Center gate of barrier.	979.7008
WA 179	Sheridan, Wyo.	Central gate in field barrier.	980.2266
WA 180	Calgary, Alberta, Can.	At entrance to parking lot inside both doors.	980.8288
WA 181	Edmonton, Alberta, Can.	Against radiator at CPA counter.	981.1729
WA 182	Ft. Nelson, B.C. Can.	Next to entrance of terminal at field.	981.6930
GW 29	Ft. St. John, B.C. Can.	Center basement room of terminal, in SE corner (pendulum station).	981.4059
WA 183	Grande Prairie, Alb., Can.	At edge of concrete in front of terminal.	981.3158
WA 184	Lethbridge, Alb., Can.	At foot of ladder to control tower on hangar E of customs.	980.7538
WA 185	Quebec, Que., Can.	On apron at edge of field opposite S end of terminal building (about 50 ft S of S field entrance to terminal) field level.	980.7405
WA 186	Vancouver, B.C., Can.	Terminal across from TCA desk, against wall (street side) at electrical outlet.	980.9299
WA 187	Watson Lake, Y.T., Can.	Inside passenger waiting room, SE corner.	981.7141
WA 188	Whitehorse, Y.T., Can.	PAA desk next to radiator.	981.7487
WA 189	Mexico City, D.F., Mex.	In corner of waiting room for incoming passengers against glass outside wall and glass partition.	977.9701
WA 190	Monterrey, N.L., Mex.	On curb at entrance to AA terminal at Inst. Geofisico Mark.	978.8617

TABLE IV. UNIVERSITY GRAVITY BASE STATIONS

Station		Station Description	Obs. Gravity
U 1119	Tuscaloosa, Ala.	*Univ. of Alabama*, U 1119, at USC&GS mark in open area, 186 ft N, 85 ft W from NW corner of Chemistry Bldg.	979.5598
GW 6	Fairbanks, Alaska	*Univ. of Alaska*, Geophysical Inst., at rear of bldg. just inside door from loading platform.	982.2462
WU 1	Berkeley, Calif.	*Univ. of California*, Sather Tower, E side of street, next to sidewalk against S abutment of wall around square.	979.9704
WU 2	Los Angeles, Calif.	*U.C.L.A.*, Chemistry-Geology Bldg., at center of doors to Room 1275.	979.5292
WU 3	Palo Alto, Calif.	*Stanford Univ.*, Lloyd Noble Laboratory for Geophysics, at rear entrance to N wing of bldg., at door stop for W door.	979.9489
WU 4	Pasadena, Calif.	*California Institute of Technology*, Mudd Hall, SW corner at top of steps.	979.5785
WU 5	San Diego, Calif.	*Institute of Oceanography*, (Scripps) Naval Electronics Laboratory, Marine Physical Lab., Post No. 5, gate house, outside of NW corner of bldg. on concrete at edge of asphalt street.	979.5502
WU 6	Boulder, Colo.	*Univ. of Colorado*, E entrance to Geology Bldg., on sidewalk at curb.	979.6193
U 1078	Colorado Springs, Colo.	*Colorado College*, Washburn Athletic Field, 160 ft N along road from NW gate.	979.4931
GW 39	Denver, Colo.	*Chamberlin Observatory*, N entrance to basement, at foot of steps	979.6114
WU 7	Golden, Colo.	*Colorado School of Mines*, on curb in front of Geology-Geophysics Science Bldg., Berthoud Hall, in line with center of front door, Illinois Street entrance.	979.5842
WU 8	New Haven, Conn.	*Yale Univ.*, Sloan Physics Laboratory, westernmost of two entrances on north side, on walk at edge of drive.	980.3163
WU 9	Atlanta, Ga.	*Georgia School of Technology*, Mechanical Engineering Bldg., N end in drive on sidewalk next to manhole, E side of bldg.	979.5286
U 36	Chicago, Ill.	*Univ. of Chicago*, 40 ft NE of NE corner Ryerson Physical Lab. on sidewalk next to curb of street. About 4 ft lower than 1st floor.	980.2858
WU 10	South Bend, Ind.	*Notre Dame Univ.*, in parking area south of Engineering Bldg., at sidewalk leading to E end bldg., about 20 ft S of line of posts.	980.2547
WA 103	West Lafayette, Ind.	*Purdue Univ.*, airport, terminal waiting room, in corner opposite door to field.	980.1469
WU 11	West Lafayette, Ind.	*Purdue Univ.*, Chemistry and Meteorology Bldg. entrance to Room 4.	980.1456
WU 12	Orone, Me.	*Univ. of Maine*, N side entrance to Boardman Hall (Engineering) 2 ft N of center of doors on step about 6 inches above ground level.	980.6063
WA 113	Bedford, Mass.	*Air Force Cambridge Research Center*, Hanscom Field, at Gate 2 to base, Bldg. 1101, outside Provost Marshall's Office, next to phone booth.	980.3942
WU 13	Boston, Mass.	*Massachusetts Institute of Technology*, Bldg. 24, SE corner of sidewalk at curb of N-S St.	980.4002
WU 14	Cambridge, Mass.	*Harvard Univ. Observatory*, (Garden St.) on flagstone terrace at south entrance against E end of steps to door.	980.4003
WU 15	Woods Hole, Mass.	*Woods Hole Oceanographic Institute*, at street entrance.	980.3271
WU 16	Ann Arbor, Mich.	*Univ. of Michigan*, at south end of parking lot just east of Natural Science Bldg., at base of flag mast, at BM (USC&GS 1934).	980.3131
WU 17	East Lansing, Mich.	*Michigan State Univ.*, Physics and Math. Bldg., at curb in front of main entrance.	980.3498
WU 18	Chapel Hill, N. C.	*Univ. of North Carolina*, new (Geology) East Hall main (south) entrance, on lower of two steps.	979.8184
GW 78	Princeton, N. J.	*Princeton Univ.*, Guyot Hall, Room 14.	980.1776
U 764	Albuquerque, N. M.	*Univ. of New Mexico*, Administration Bldg., 52 ft N of S wall and 40 ft E of E wall.	979.2232
WU 19	Socorro, N. M.	*New Mexico Institute of Mining & Technology*, NW corner of Geophysical Research Lab., at inside corner of two sidewalks, at BM R222.	979.1856
WU 20	New York, N. Y.	*Columbia Univ.*, Schermerhorn Hall, sidewalk outside of hall by large green door on Amsterdam Ave. across from 118th St. corner.	980.2689
GW 1	Palisades, N. Y.	*Lamont Geological Observatory*, gravity room in basement.	980.2596
WU 21	Syracuse, N. Y.	*Syracuse Univ.*, at corner about 100 ft N of Steele Hall, on sidewalk, at curb, 10 ft N of boulder marking tree commemorating birth of Mme. Marie Sklodowska Curie.	980.3817

(*Continued on next page*)

TABLE IV. (*Continued*)

Station			Station Description	Obs. Gravity
WU	22	Columbus, Ohio	*Ohio State Univ.*, Research Center, main gate on sidewalk beside guard-house.	980.0961
WU	23	Columbus, Ohio	*Ohio State Univ.*, Bldg. 24, Hardin Rd., washroom under S window.	980.0993
GW	51	Tulsa, Okla.	*Tulsa Univ.*, Phillips Engineering Bldg., Room 7A, back wall against radiator, 28 ft from front of bldg. and 8 ft W of E wall. (pend. sta.)	979.7663
WU	24	Tulsa, Okla.	*Tulsa Univ.*, at E front entrance to Phillips Engineering Bldg.	979.7660
U	957	Philadelphia, Pa.	*Univ. of Pennsylvania*, Franklin Stadium, at brass disk in brick wall at N corner of field. (pend. sta.)	980.1974
WU	25	State College, Pa.	*Pa. State Univ.*, State College, at curb (street level) in front of main entrance to Mineral Sciences Bldg.	980.1282
WU	26	Knoxville, Tenn.	*Univ. of Tennessee*, Ayers Hall, main entrance on flagpole side, on concrete center of entrance.	979.7120
WU	27	Houston, Texas	*Rice Univ.*, Physics Bldg., parking lot, on concrete platform (ground level) for nitrogen generator, 6 ft E of W edge of concrete at edge of asphalt.	979.2988
WU	28	Salt Lake City, Utah	*Univ. of Utah*, Mines Building, center entrance on E side of sidewalk at road.	979.7851
WU	29	Salt Lake City, Utah	*Liberty Park*, under large tree used as base station by Univ. of Utah Geophysics Dept.	979.8001
WU	30	Burlington, Vt.	*Univ. of Vermont*, Williams Science Hall, at main entrance to bldg., on walk at center of entrance against lower step.	980.5155
WU	31	Blacksburg, Va.	*Virginia Polytech. Institute*, Holden Hall (Geology) on curb of walk to main entrance three short flights of steps below main entrance, about 100 ft SE of and on center line of main entrance.	979.7324
WU	32	Seattle, Wash.	*Univ. of Washington*, Johnson Hall, Room B1.	980.7389
GW	3	Madison, Wis.	*Univ. of Wisconsin*, Science Hall, entrance to Room 40.	980.3689
WU	33	Madison, Wis.	*Univ. of Wisconsin*, Geophysics Research Center, 2544 University Ave., at front door.	980.3661
WU	34	Lawrence, Kan.	*University of Kansas*, Lindley Hall, on first step outside northeast entrance on left end of step facing door.	979.9845
WU	35	Lawrence, Kan.	*University of Kansas*, Hoch Auditorium, on sidewalk in front of main entrance.	979.9849
WU	36	Emory, Ga.	*Emory University*, pier in basement of Physics Building.	979.5375
WU	37	Emory, Ga.	*Emory University*, east rear entrance to Geology Building on concrete slab outside door.	979.5390
WU	38	Knoxville, Tenn.	*University of Tennessee*, at bench mark Z189 at entrance to Physics-Geology Building.	979.7120
GW	25	Edmonton, Alberta, Can.	*Univ. of Alberta*, Physics Lab (Room 19) pend. sta. in SW corner of lab.	981.1678
GW	43	Mexico City, D.F., Mex.	*Univ. of Mexico*, in the gravity room at the Universidad Nacional de Mexico, about 50 ft N of the building housing the Van de Graaf generator of the Physics Department. On 1st pier to rt.	977.9414
GW	41	Mexico City, D.F., Mex.	*Tacubaya*, Photogrammetry room of the Oficina de Geografia, 192 Observatory Ave., 6 ft W of the No. 1 pend. pier.	977.9419
GW	21	Monterrey, N.L., Mex.	*Institute Technologico y de Estudios Superiores*, classroom for auto shop repairs, 10 ft from the N (outside) wall and 3 ft from the E wall of the room.	978.8055
WU	39	Austin, Texas	*LaCoste and Romberg Laboratory*, on floor next to pier nearest the door.	979.2849

and in Figure 5 the differences are plotted as a function of change in gravity. As the datum value used by the U. S. Coast and Geodetic Survey is 0.8 mgal lower than that adopted by the writers, the values cited for the present study should average this amount higher than those given by Duerksen (1948). All comparisons are for the observation sites used by the U. S. Coast and Geodetic Survey. Although in some instances exact reoccupations were not possible, the writers have corrected their values so as to correspond to that to be expected at the pendulum site. The uncertainty in these corrections for difference in position and elevation is not believed to be greater than 0.2 mgal.

From an inspection of Table XI it appears that the pendulum results are characterized by random errors in the amount of ± 2 to 3 mgals with a mean

TABLE V. GRAVIMETER OCCUPATIONS OF PENDULUM STATIONS

Station	Pend. Sta.	Station Description	Obs. Gravity
Tuscaloosa, Ala.	U 1119	Univ. of Alabama at USC&GS mark in open area. 186 ft N., 85 ft W from NW corner of Chemistry Bldg.	979.5598
Fairbanks, Alaska	GW 27	Ladd AFB, BOQ 10, Bldg. 1157, SW corner of bldg. in basement at foot of stairs.	982.2444
Pt. Barrow, Alaska	GW 105	Butler Bldg. No. 353, SW corner.	982.6997
Eureka, Calif.	U 238	On N corner (P.O.) of H & 5th Sts. at traffic signal, 6 ft above pend. sta.	980.2219
Oceanside, Calif.	U 241	E corner of 1st & Horne Sts., at high school, on curb next to hydrant.	979.5663
San Francisco, Calif.	GW 54	Academy of Science, Golden Gate Park, Paleo. Lab.	979.9867
Santa Rosa, Calif.	U 239	Post office, N corner of 5th & A Sts., next to fire alarm box, 25 ft S of BM V106.	980.0203
Ventura, Calif.	U 250	Courthouse, NE corner, on landing at top of steps to basement.	979.5600
Colorado Springs, Colo.	U 1078	Washburn Athletic Field of Colorado College, 160 ft N along dirt road from NW gate.	979.4931
Craig, Colo.	U 1164	Rodeo grounds, .19 miles S US 40 and 43 yds W of gravity mark on E fence line.	979.6202
Denver, Colo.	GW 39	Chamberlin Observatory, N entrance to basement, at foot of steps.	979.6114
Washington, D. C.	U 337a	Department of Commerce Building, 14th St. side, N arch of parking area, at bench mark, on curb.	980.1182
Crestview, Fla.	U 890	1.0 miles W of courthouse, at Mar Camp tourist court, on left (S) side of US 90, 370 ft S of center US 90 and 91 ft E of blacktop road. Std. grav. mark.	979.3815
Lake City, Fla.	U 869	Duval Tourist Court, .9 miles E center of town on US 90. About 30 ft N of S prop. line and 121 ft W of USC&GS mark on E prop. line.	979.3340
Mariana, Fla.	U 399	High school, NE corner of grounds, 12 ft W of USGS mark on W curb of Daniel St.	979.3665
Pensacola, Fla.	U 164	NE corner of courthouse in drive, about 20 ft N of bldg. 5 ft above U 164 level.	979.3631
Atlanta, Ga.	U 15	Service entrance to capitol on main sidewalk.	979.5238
Chicago, Ill.	U 36	Univ. of Chicago, 40 ft NE of NE corner Ryerson Physical Lab., on sidewalk next to curb of street. About 4 ft lower than 1st floor.	980.2858
Indianapolis, Ind.	U 137	Sidewalk of court house on Meridian Street opposite SW corner of bldg. at same level as basement.	980.0898
Beloit, Kan.	GW 52	Saults Service Station, on concrete platform in front of bldg. at right edge (facing in) of platform, 2 ft from door. About 7 ft above and 25 ft SE of basement station.	979.9978
Baltimore, Md.	U 23A	Corner of Monument and Linden, NW corner of parking lot about 30 ft E of bldg. and against brick wall. Mark in corner.	980.1164
Boston, Mass.	U 29	Annex to state house, in NE corner of basement, in vault.	980.3967
Cambridge, Mass.	U 30	Harvard Observatory (Garden St.) in basement room, 2 ft N of foundation of telescope.	980.4011
Laurel, Miss.	U 145	Corner of 5th St. and 4th Ave. At 4th Ave. entrance to school on sidewalk at curb.	979.4697
Billings, Mont.	GW 35	Airport, W wall of Hangar No. 2, 7 ft of N door.	980.3710
Cut Bank, Mont.	GW 34	Airport, field door of customs inspection room.	980.6085
Forsyth, Mont.	U 584	At courthouse, at top of stairs to NW basement entrance at ground level 8 ft above pend. sta.	980.5089
Great Falls, Mont.	GW 4	Roosevelt School, 20 ft N of S entrance of S hall in hall.	980.5270
Albuquerque, N. M.	U 764	Univ. of N. Mex., Administration Bldg., 52 ft N of S wall and 40 ft E of E wall.	979.2232
Wilmington, N. C.	U 149	In parking lot back of courthouse at Princess & 3rd St. 30 ft N of brick wall at edge of drive and 40 ft W of SW corner of new addition to courthouse.	979.6703
Columbus, Ohio	U 136	Old Memorial Hall on Broad St., N end of bldg. under archway in center. About 11 ft above pend. sta.	980.0864
Tulsa, Okla.	GW 51	Phillips Engineering Bldg. Rm. 7A, back wall against radiator. 28 ft from front of bldg. and 8 ft W of E wall.	979.7663
Eugene, Ore.	U 232	Public Library on Olive St. curb 40 ft S of W 13th St. curb, about 100 ft N and 1 ft below pend. sta.	980.4910

(*Continued on next page*)

TABLE V. (*Continued*)

Station	Pend. Sta.		Station Description	Obs. Gravity
Portland, Ore.	U	229	US customhouse, near NW corner, on Everret St. sidewalk 40 ft W of 8th St. curb, 5 ft above pend. sta.	980.6474
Philadelphia, Pa.	U	957	Inside Franklin Stadium, Univ. of Pa., at brass disk in brick wall at N corner of field.	980.1974
Charleston, S. C.	U	17	Old Citadel, SW corner on sidewalk. Probably 3 ft below level of pend. sta.	979.5501
Aberdeen, S. D.	U	186	At SE corner of 4th St. and Main, at curb, on sidewalk, at J. C. Penny Co. (site of old post office).	980.5463
Cleveland, Tenn.	U	153	P.O. on sidewalk at curb opposite SW corner of bldg. about 1 ft below basement floor.	979.6517
Alpine Texas	U	98	Public School at N end of 6th St., 3 ft from edge of sidewalk at W entrance.	978.9910
Corpus Christi, Texas	U	727	3314 Hamilton Rd., on sidewalk at property line next to pole, SW corner of property.	979.1489
Del Rio, Texas	U	723	Camp Del Rio, sidewalk at entrance to Cabin No. 23.	979.1920
Denison, Texas	U	73A	NE corner of Armstrong and Main Sts., on curb of Armstrong 30 ft N of curb of Main.	979.5712
El Paso, Texas	U	63	School at N Kansas & Arizona, on sidewalk curb Kansas St. entrance.	979.1257
Galveston, Texas	U	7	On curb of parking lot on sidewalk to rear entrance of West and South Life Insurance Co. between 22nd and 21st Sts. and G & H Aves.	979.2753
Houston, Texas	GW	18	Hall-Sears, 2424 Branard St. at car shelter.	979.2985
Rosenberg, Texas	U	730	Fairview Tourist Court, Hy. US 59 and US 90A. On sidewalk to southwesternmost cabin, at mark.	979.2788
Salt Lake City, Utah	U	49	Inside Temple Square, SE corner of grounds on top of sandstone block engraved: "United States Meridian Line," about 50 ft N of and midway between log cabin and museum.	979.8038
Vernal, Utah	U	1175	Airport, 225 ft E of entrance to field and 90 ft S of section line road, in open field.	979.6686
Lexington, Va.	U	175	On sidewalk at Nelson St. entrance to P.O. at bottom of steps.	979.8641
Bellingham, Wash.	U	220	Corner of W. Magnolia & Cornwall, at post office, on Magnolia St. curb, 20 ft from S corner of bldg.	980.8855
Bremerton, Wash.	U	226	Smith School, at SW corner of bldg. next to window, ground level.	980.8117
Everett, Wash.	U	221	P.O. at Wall & Colby St., NW corner of bldg. on sidewalk, about 6 ft above pend. sta.	980.7807
Issaquah, Wash.	U	222	At junior high school on sidewalk at rear of building opposite top of steps to basement.	980.7654
Olympia, Wash.	U	112	SE corner Quince & 5th St., on curb.	980.8170
Port Angeles, Wash.	U	223	Courthouse, at E wall, 10 ft S of N wall, on concrete drive, approx. 5 ft above pend. sta.	980.8752
Madison, Wis.	U	37	Science Hall, University of Wisconsin, entrance to Room 40.	980.3689
Calgary, Alb., Can.	GW	32	Airport, Aux. Gen. Bldg. approx. 100 ft S. Chinook hangar SW rooms.	980.8281
Edmonton, Alb., Can.	GW	25	Univ. of Alberta, Physics Lab. (Rm. 19) pend. sta. in SW corner of lab.	981.1678
Ft. St. John, B.C., Can.	GW	29	Airport, in center basement room of terminal in SE corner.	981.4059
Watson Lake, Y.T., Can.	GW	8	Airport, inside passenger waiting room, SE corner.	981.7141
Whitehorse, Y.T., Can.	GW	26	In pumphouse approx. 100 ft E SE corner of hangar at foot of steps.	981.7486
Mexico City, D.F., Mex.	GW	43	In gravity room at Universidad Nacional de Mexico, about 50 ft N of bldg. housing the Van de Graaf generator of the Physics Department.	977.9414
Mexico City, D.F., Mex.	GW	41	Photogrammetry room of the Oficina de Geografia, 192 Observatory Ave., Tacubaya, about 20 ft W of pier, floor level.	977.9419
Monterrey, N.L., Mex.	GW	21	Institute Technology, auto shop classroom, at mark in floor: Instituto Geofisico Estacian UNAM about 15 ft S of N wall center of room.	978.8055
Paso de Cortes, Mex.	GW	42	TV relay station on floor in center of bldg. between banks of equipment.	977.5711

TABLE VI. HARBOR GRAVITY BASE STATIONS

Station		Station Description	Obs. Gravity
WH 1	Milwaukee, Wis.	Milwaukee dock area, Clipper Ferry landing bldg. at water's edge, in parking area, about 30 ft east of bldg. and about 80 ft east of car loading ramp to ferry. (Wis.-Mich. SS Co.)	980.3697
WH 2	Chicago, Ill.	Chicago sanitary causeway (approx. 100 yds. north Columbia Yacht Club) at entrance to causeway, at rear of Chicago Naval Armory, about 7 ft above lake level, about 25 ft west of gate to causeway and 25 ft south of north edge of Navy pier.	980.2941
WH 3	Toledo, Ohio	Toledo, USCG sta., at pier, at southeast corner, about 40 ft from end and 20 ft N of S side, about 5 ft above water.	980.2528
WH 4	Cleveland, Ohio	USCG sta., (end of 9th St.) at NE corner of pier about 5 ft from each edge, about 7 ft above lake, next to ring buoy on light pole.	980.2502
WH 5	Quebec, Can.	Pier of Canada SS Lines, west end of pier, 75 ft out from 40 Dalhousie Rue. Hy. 2 runs into driveway.	980.7476
WH 6	Portland, Me.	U. S. Naval Res. Training Center, at concrete base of Naval Reserve pier.	980.5216
WH 7	Portsmouth, N. H.	Navy base, Berth No. 5. SE corner, about 20 ft from S edge of pier, about 10 ft from W edge.	980.4727
WH 8	Boston, Mass.	Boston Naval Base, Pier No. 7, sea end, about 40 ft from end and 30 ft from west side.	980.4040
WH 9	Woods Hole, Mass.	Woods Hole USCG pier, SE corner, about 35 ft N of S edge and 35 ft W of E edge.	980.3276
WH 10	Woods Hole, Mass.	Woods Hole, WHOI pier, on concrete 30 ft SE of tide station.	980.3270
WH 11	Davisville, R. I.	Pier No. 1 at sea end, 6 ft from end, on center line of pier.	980.3123
WH 12	Quonset Pt., R. I.	NAS, on curb in front of BOQ on center line.	980.3111
WH 13	New London, Conn.	Submarine Base, Pier No. 7, north (land) end, at base of light post on E side.	980.2964
WH 14	New York, N. Y.	New York Naval Yard, Pier J, NE corner (sea end) 15 ft S of N end, against wood beam at E side, Berth 16.	980.2721
WH 15	Philadelphia, Pa.	Philadelphia Navy Yard, Pier No. 5, center of pier about 25 ft from south (sea) end.	980.1999
WH 16	Baltimore, Md.	USCG depot, sea end, Pier No. 3, about 30 ft N of S end and 25 ft E of W side.	980.1046
WH 17	Norfolk, Va.	Norfolk Naval Base, Pier 5, sea end, 5 ft in (NE) from end on center line of pier.	979.8843
WH 18	Wilmington, N. C.	USCG station, at pier on concrete center of main entrance from street, 3 ft from land edge of wood pier.	979.6708
WH 19	Charleston, S. C.	Naval Base, Pier F at outer end, 30 ft N of end and 10 ft W of outer side.	979.5650
WH 20	Savannah, Ga.	USCG station, about 30 ft E of wire fence barrier gate and 10 ft in from edge.	979.4932
WH 21	Jacksonville, Fla.	Mayport Naval Base, north pier, Berth C-1, S side of pier, on concrete 20 ft N of asphalt at indentation in pier.	979.3758
WH 22	Pensacola, Fla.	NAS, Alleghany Pier, NE corner, 5 ft S of N edge and 10 ft W of E edge.	979.3560
WH 23	Mobile, Ala.	USCG pier, 25 ft N of S side and 100 ft from sea end.	979.3576
WH 24	New Orleans, La.	USCG New Carol Light Station, sea end of pier 20 ft S of bell.	979.3310
WH 25	Galveston, Texas	USCG station, McKenzie (Hopper Dredge Dock) on road to dock, 10 ft in from land edge of pier.	979.2789
WH 26	Corpus Christi, Texas	City dock, S end, 21 ft N of tank and about 40 ft E of street edge.	979.1490
C 553	San Diego, Calif.	USN Sonar School, at junction of Piers No. 5 and 6 on concrete next to manhole cover. El. 10.97 ft., Columbia 1948 No. 553.	979.5423
WH 27	LaJolla, Calif.	Scripps Inst. of Oceanography, Naval Electronics Lab, Marine Physical Lab, Post No. 5 gate house, outside at NW corner of bldg. on concrete at edge of asphalt street.	979.5502
WH 28	Port of Los Angeles, Calif.	San Pedro, Port of Los Angeles, Berth 57, at SW side of pier, land end, next to large green mooring cleat.	979.6495
WH29	Monterey, Calif.	USCG pier, sea end, at base of steel tower.	979.8917
WH 30	San Francisco, Calif.	USN shipyard, Berth No. 3, NE end of berth at edge and corner marked "O".	979.9906
WH 31	Bremerton, Wash.	Puget Sound Naval Shipyard, Pier 5, sea end, 6 ft N of S end, 10 ft E of W side.	980.8239

TABLE VII. L&R GEODETIC NO. 1 AIRPORT STATIONS

	Station	Lat.	Long.	Elev.	Observed Gravity	Free Air Anomaly	Bouguer Anomaly
WA 81	Birmingham, Ala.	33 34.1	86 45.0	643	979.5390	−26.0	−47.9
WA 82	Mobile, Ala.	30 41.3	88 14.2	217	979.3396	−31.8	−39.2
WA 83	Los Angeles, Calif.	33 56.1	118 23.0	109	979.5946	−51.1	−54.8
WA 84	Monterey, Calif.	36 35.5	121 50.5	220	979.8692	+8.2	+0.7
WA 85	San Diego, Calif.	32 44.0	117 11.0	14	979.5369	−18.3	−18.8
WA 86	San Francisco, Calif. (Gate 23)	37 37.0	122 22.8	10	979.9883	+18.6	+18.3
WA 87	San Francisco, Calif. (Main entrance)	37 37.0	122 22.8	10	979.9885	+18.8	+18.5
WA 88	Santa Barbara, Calif.	34 26.0	119 49.5	14	979.6407	−55.7	−56.2
WA 89	Denver, Colo. (Gate 2)	39 45.6	104 53.0	5,325	979.6335	−24.8	−206.2
WA 90	Denver, Colo. (Gate 6)	39 45.6	104 53.0	5,325	979.6327	−25.6	−207.0
WA 91	Kremling, Colo.	40 3.5	106 22.6	7,411	979.4903	+1.7	−250.8
WA 92	New Haven, Conn.	41 16.0	72 53.3	4	980.3125	+19.5	+19.3
WA 93	Wilmington, Del.	39 45.9	75 36.5	135	980.1757	+28.8	+24.2
WA 7	Washington, D. C. (Field level)	38 51.0	77 1.3	10	980.1098	+32.0	+31.7
WA 8	Washington, D. C. (Upper street level)	38 51.1	77 1.8	16	980.1088	+31.4	+30.9
WA 94	Jacksonville, Fla.	30 25.5	81 38.5	52	979.3856	+19.4	+17.7
WA 95	Pensacola, Fla.	30 28.8	87 11.2	121	979.3630	−1.0	−5.1
WA 96	Tallahassee, Fla.	30 26.3	84 20.0	70	979.3544	−11.1	−13.5
WA 97	Atlanta, Ga. (East Concourse)	33 39.1	84 25.3	1,005	979.5205	−17.3	−51.6
WA 98	Atlanta, Ga. (West Concourse)	33 39.1	84 25.3	1,005	979.5203	−17.5	−51.8
WA 99	Savannah, Ga.	32 1.7	81 8.0	40	979.4980	+2.7	+1.3
WA 100	Coeur d'Alene, Idaho	47 46.2	116 49.0	2,310	980.6387	−23.1	−101.8
WA 101	Chicago, Ill.	41 47.7	87 45.1	618	980.2864	+3.8	−17.3
WA 102	Indianapolis, Ind.	39 43.6	86 16.0	792	980.0933	+11.6	−15.4
WA 103	W. Lafayette, Ind.	40 25.0	86 56.0	605	980.1469	−13.7	−34.3
WA 104	Beloit, Kan.	39 28.2	98 8.0	1,416	980.0000	−0.3	−48.5
WA 105	Kansas City, Kan.	39 8.7	94 36.0	746	980.0010	−33.6	−59.0
WA 106	Wichita, Kan.	37 37.7	97 16.0	1,372	979.8404	−2.2	−48.9
WA 107	Lexington, Ky.	38 6.6	84 28.0	910	979.8988	−29.3	−60.3
WA 108	Baton Rouge, La.	30 31.8	91 9.3	70	979.3637	−9.0	−11.4
WA 109	New Orleans, La. (Entrance to term.)	30 2.3	90 2.0	8	979.3312	−8.8	−9.1
WA 110	New Orleans, La. (Moisant Airport)	29 59.6	90 15.7	3	979.3298	−7.1	−7.3
WA 111	Portland, Me.	43 38.8	70 18.4	60	980.5126	−11.0	+8.9
WA 112	Baltimore, Md.	39 15.0	76 30.9	10	980.1104	−2.7	−3.0
WA 113	Bedford, Mass.	42 28.2	71 17.0	135	980.3942	+5.6	−1.0
WA 114	Boston, Mass. (Gate 17)	42 22.0	71 1.1	12	980.4036	+12.7	+12.3
WA 115	Boston, Mass. (Gate 19)	42 22.0	71 1.1	12	980.4036	+12.7	+12.3
WA 116	Detroit, Mich.	42 14.0	83 32.0	715	980.3188	+6.0	−18.4
WA 117	Lansing, Mich.	42 46.5	84 35.8	858	980.3518	+3.7	−25.5
WA 118	Minneapolis, Minn.	44 53.2	93 13.2	840	980.5950	+54.9	+26.2
WA 119	Meridian, Miss.	32 20.4	88 44.8	297	979.4840	−12.5	−22.6
WA 120	Kansas City, Mo.	39 7.2	94 35.6	744	979.9998	−32.8	−58.1
WA 121	St. Louis, Mo.	38 45.0	90 22.0	567	980.0043	−12.3	−31.6
WA 122	Billings, Mont.	45 48.0	108 32.2	3,612	980.3717	+9.8	−113.2
WA 123	Butte, Mont.	45 57.2	112 29.2	5,554	980.1744	−18.6	−207.8
WA 124	Great Falls, Mont.	47 29.0	111 22.0	3,671	980.5137	+5.7	−119.4
WA 125	Cut Bank, Mont.	48 36.0	112 22.0	3,900	980.6085	+21.7	−111.1
WA 126	Lewistown, Mont.	47 2.5	109 28.9	4,209	980.4510	+33.3	−110.1
WA 127	Missoula, Mont.	46 55.0	114 5.4	3,203	980.4440	−57.0	−166.2
WA 128	Las Vegas, Nev.	36 4.2	115 10.0	2,171	979.6049	−27.7	−101.6
WA 129	Reno, Nev.	39 29.5	119 45.5	4,404	979.6873	−33.9	−183.9
WA 130	Albuquerque, N. M.	35 2.5	106 36.9	5,330	979.2081	−39.6	−221.2
WA 131	Santa Fe, N. M.	35 37.4	106 5.2	6,344	979.1974	−4.4	−220.6
WA 132	New York, N. Y. (LaGuardia)	40 46.7	73 52.8	19	980.2825	+34.5	+33.9
WA 133	New York, N. Y. (Idlewild)	40 38.6	73 47.0	15	980.2261	−10.2	−10.7
WA 134	Syracuse, N. Y.	43 4.4	76 15.5	396	980.3968	−21.6	−35.1
WA 135	Cincinnati, Ohio (Front of terminal)	39 3.3	84 39.7	890	979.9935	−19.6	−49.9
WA 136	Cincinnati, Ohio (Gate 3)	39 3.3	84 39.7	896	979.9931	−19.4	−49.9
WA 137	Cleveland, Ohio	41 24.5	81 50.7	789	980.2322	+0.3	−26.6
WA 138	Columbus, Ohio	40 00.4	82 52.2	816	980.0791	−25.1	−53.0
WA 139	Tulsa, Okla.	36 12.2	95 54.1	674	979.7766	−8.2	−31.2
WA 140	Eugene, Ore.	44 7.2	123 13.2	365	980.5148	−0.8	−13.3
WA 141	Medford, Ore.	42 22.2	122 52.2	1,330	980.2375	−29.7	−75.1
WA 142	Portland, Ore. (Lower lobby)	45 35.0	122 36.0	23	980.6483	−31.6	−32.4

TABLE VII. (*Continued*)

	Station	Lat.	Long.	Elev.	Observed Gravity	Free Air Anomaly	Bouguer Anomaly
WA 143	Portland, Ore. (Old Terminal)	45 35.0	122 36.0	30	980.6477	−31.5	−32.5
WA 144	Philadelphia, Pa.	39 53.6	75 10.0	12	980.1976	+27.7	+27.3
WA 145	Pittsburgh, Pa.	40 29.5	80 13.8	1,168	980.0993	−15.1	−54.9
WA 146	Providence, R. I.	41 43.7	71 25.5	53	980.3139	−15.9	−17.7
WA 147	Charleston, S. C. (MATS Terminal)	32 54.0	80 2.4	45	979.5674	+1.4	−0.1
WA 148	Charleston, S. C. (Municipal Airport)	32 53.9	80 2.4	40	979.5668	+0.5	−0.9
WA 149	Chattanooga, Tenn.	35 2.3	85 12.5	682	979.6505	−34.1	−57.4
WA 150	Knoxville, Tenn.	35 48.9	83 59.0	989	979.7032	−18.7	−52.4
WA 151	Austin, Texas	30 17.8	97 42.3	631	979.2889	−12.7	−34.2
WA 152	Brownsville, Texas	25 54.8	97 25.3	22	979.0509	+19.7	+19.0
WA 153	Corpus Christi, Texas	27 46.0	97 26.2	42	979.1430	−20.7	−22.1
WA 154	Dallas, Texas	32 51.0	96 51.3	477	979.5131	−8.2	−24.4
WA 155	El Paso, Texas	31 48.2	106 23.8	3,936	979.0814	−29.3	−163.4
WA 156	Ft. Worth, Texas	32 48.8	97 22.1	692	979.4934	−4.6	−28.2
WA 157	Galveston, Texas	29 16.0	94 51.6	7	979.2696	−10.7	−11.0
WA 158	Houston, Texas (Gate 9)	29 39.0	95 16.7	50	979.2933	−12.5	−14.2
WA 159	Houston, Texas (Gate 7)	29 39.0	95 16.7	50	979.2932	−12.6	−14.3
WA 160	Laredo, Texas	27 32.2	99 27.4	512	979.0792	−23.3	−40.7
WA 161	San Antonio, Texas (American Airlines)	29 32.0	98 28.0	800	979.1973	−29.0	−56.2
WA 162	San Antonio, Texas (Gate 8)	29 32.0	98 28.0	797	979.1975	−29.1	−56.2
WA 163	Salt Lake City, Utah	40 46.8	111 58.3	4,220	979.8070	−46.0	−189.8
WA 164	Vernal, Utah	40 26.3	109 31.4	5,277	979.6686	−54.5	−234.3
WA 165	Burlington, Vt.	44 28.1	73 9.2	333	980.5181	−32.0	−43.3
WA 166	Norfolk, Va. (New Terminal)	36 53.5	76 12.0	26	979.8789	−26.3	−27.1
WA 167	Norfolk, Va. (Old Station)	36 53.5	76 12.0	26	979.8788	−26.4	−27.2
WA 168	Roanoke, Va.	37 19.3	79 58.0	1,174	979.8076	−26.9	−66.9
WA 169	Port Angeles, Wash.	48 7.4	123 29.6	290	980.8640	−19.6	−29.5
WA 170	Seattle, Wash. (Gate 5)	47 26.5	122 18.0	416	980.7765	−34.0	−48.1
WA 171	Seattle, Wash. (Gate 3)	47 26.5	122 18.0	416	980.7765	−34.0	−48.1
WA 172	Seattle, Wash. (At curb)	47 26.5	122 18.0	416	980.7765	−34.0	−48.1
WA 173	Spokane, Wash.	47 37.2	117 31.9	2,372	980.6463	+3.8	−77.0
WA 174	Charleston, W. Va.	38 22.3	81 35.4	981	979.9259	−18.5	−51.9
WA 175	Janesville-Beloit, Wis.	42 37.1	89 2.0	807	980.3303	−8.5	−36.0
WA 176	Milwaukee, Wis.	42 57.2	87 54.0	675	980.3597	−21.6	−44.6
WA 177	Casper, Wyo.	42 54.5	106 28.0	5,347	979.9562	+18.4	−163.8
WA 178	Cheyenne, Wyo.	41 9.5	104 48.5	6,156	979.7008	−3.9	−213.6
WA 179	Sheridan, Wyo.	44 46.5	106 58.0	4,021	980.2266	−4.3	−141.3
WA 180	Calgary, Alberta, Can.	51 6.2	114 1.0	3,540	980.8288	−14.7	−135.3
WA 181	Edmonton, Alberta, Can.	53 34.4	113 31.8	2,185	981.1729	−13.9	−88.4
WA 182	Ft. Nelson, B.C., Can.	58 50.5	122 36.0	1,247	981.6930	−21.8	−64.3
WA 183	Grande Prairie, Alb., Can.	55 10.8	118 53.0	2,200	981.3158	−7.1	−82.1
WA 184	Lethbridge, Alb., Can.	49 37.8	112 48.0	3,030	980.7538	−6.9	−110.1
WA 185	Quebec, Que., Can.	46 47.4	71 23.0	235	980.7405	−28.3	−36.3
WA 186	Vancouver, B.C., Can.	49 11.2	123 11.0	6	980.9299	−75.6	−75.9
WA 187	Watson Lake, Y.T., Can.	60 7.2	128 48.0	2,230	981.7141	−9.4	−85.4
WA 188	Whitehorse, Y.T., Can.	60 42.0	135 5.0	2,297	981.7487	−13.6	−91.9
WA 189	Mexico City, D.F., Mex.	19 25.5	99 6.0	7,347	977.9701	+42.3	−208.0
WA 190	Monterrey, N.L., Mex.	25 53.0	100 14.0	1,474	978.8617	−30.8	−81.0

error with regard to sign of about +1.0 mgal. If the difference in datum is taken into consideration this mean error becomes approximately +2.0 mgals. This is brought out in Figure 5 where the differences are plotted with both sets of data on the same datum. From this plot it might be concluded that there is evidence for a systematic deviation with change in gravity of about 5 mgals per 1,000 mgal change. This is believed to be fortuitous for Woollard et al. (1955) have shown that there is good evidence for datum shifts in the U. S. Coast and Geodetic Survey pendulum stations results that can be correlated with different operational seasons. For example, Table XII lists the changes observed at 36 pendulum sites occupied by Woollard in the midwest area as a function of the year of observation. If the present comparison involving different pendulum stations (Table XI) is studied in the same manner, the results are as shown in Table XIII. The agreement

TABLE VIII. PRINCIPAL FACTS PENDULUM STATIONS (REOCCUPIED)

Station		Lat.	Long.	Elev.	Observed Gravity	Free Air Anomaly	Bouguer Anomaly
Tuscaloosa, Ala.	U 1119	33 12.7	87 32.7	229	979.5598	−14.6	−22.4
Fairbanks, Alaska	GW 27	64 50.6	147 37.0	444	982.2444	+2.9	−12.2
Pt. Barrow, Alaska	GW 105	71 19.6	156 40.6	11	982.6997	+11.8	+11.4
Eureka, Calif.	U 238	40 48.2	124 9.7	45	980.2219	−25.9	−27.4
Oceanside, Calif.	U 241	33 11.6	117 22.5	127	979.5663	−16.1	−20.5
San Francisco, Calif.	GW 54	37 46.2	122 28.2	242	979.9867	+25.5	+17.2
Santa Rosa, Calif.	U 239	38 26.4	122 43.0	157	980.0203	−7.6	−12.9
Ventura, Calif.	U 250	34 16.8	119 17.6	78	979.5600	−117.5	−120.2
Colorado Springs, Colo.	U 1078	38 50.9	104 49.7	6,011	979.4931	−20.1	−224.9
Craig, Colo.	U 1164	40 30.8	107 32.1	6,183	979.6202	−24.4	−235.0
Denver, Colo.	GW 39	39 40.6	104 57.1	5,379	979.6114	−34.4	−217.7
Washington, D. C.	U 337A	38 56.6	77 3.4	287	980.1182	+58.2	+48.5
Crestview, Fla.	U 890	30 45.8	86 35.3	168	979.3815	−0.4	−6.2
Lake City, Fla.	U 869	30 11.3	82 37.3	190	979.3340	−0.6	−7.1
Mariana, Fla.	U 399	30 46.5	85 14.1	167	979.3665	−16.5	−22.2
Pensacola, Fla.	U 164	30 24.5	87 12.9	109	979.3631	+3.6	−0.1
Atlanta, Ga.	U 15	33 45.3	84 23.5	1,063	979.5238	−17.2	−53.4
Chicago, Ill.	U 36	41 47.4	87 35.9	593	980.2858	+1.3	−18.9
Indianapolis, Ind.	U 137	39 45.9	86 8.8	713	980.0898	−2.8	−27.0
Beloit, Kan.	GW 52	39 27.1	98 6.2	1,372	979.9978	−5.0	−51.7
Baltimore, Md.	U 23A	39 17.8	76 37.3	100	980.1164	+7.7	+4.3
Boston, Mass.	U 29	42 21.6	71 3.8	72	980.3967	+12.0	+9.6
Cambridge, Mass.	U 30	42 22.8	71 7.8	46	980.4011	+12.2	+10.6
Laurel, Miss.	U 145	31 41.7	89 7.8	265	979.4697	+22.5	+13.4
Billings, Mont.	GW 35	45 48.2	108 32.5	3,614	980.3710	+9.0	−114.1
Cut Bank, Mont.	GW 34	48 37.0	112 22.5	3,899	980.6085	+20.1	−112.7
Forsyth, Mont.	U 584	46 16.2	106 39.9	2,512	980.5089	+1.2	−84.4
Great Falls, Mont.	GW 4	47 30.7	111 15.7	3,445	980.5270	−4.8	−122.2
Albuquerque, N. M.	U 764	35 5.1	106 37.4	5,154	979.2232	−44.8	−220.4
Wilmington, N. C.	U 149	34 14.2	77 56.6	28	979.6703	−8.3	−9.2
Columbus, Ohio	U 136	39 57.8	82 59.4	769	980.0864	−18.5	−44.7
Tulsa, Okla.	GW 51	36 9.1	95 56.5	768	979.7663	−5.2	−31.4
Eugene, Ore.	U 232	44 2.7	123 5.6	422	980.4910	−12.5	−26.9
Portland, Ore.	U 229	45 31.4	122 40.7	21	980.6474	−27.3	−28.0
Philadelphia, Pa.	U 957	39 57.0	75 11.4	41	980.1974	+25.2	+23.8
Charleston, S. C.	U 17	32 47.2	79 56.0	17	979.5501	−9.2	−9.8
Aberdeen, S. D.	U 186	45 27.5	98 29.0	1,305	980.5463	−1.7	−46.2
Cleveland, Tenn.	U 153	35 9.4	84 52.9	863	979.6517	−26.0	−55.4
Alpine, Texas	U 98	30 21.5	103 39.7	4,462	978.9910	+44.9	−107.1
Corpus Christi, Texas	U 727	27 49.2	97 23.3	4	979.1489	−22.3	−22.5
Del Rio, Texas	U 723	29 21.8	100 53.2	956	979.1920	−6.5	−39.1
Denison, Texas	U 73A	33 45.4	96 32.8	767	979.5712	+2.2	−23.9
El Paso, Texas	U 63	31 46.3	106 29.0	3,759	979.1257	+0.9	−127.1
Galveston, Texas	U 7	29 18.2	94 47.5	8	979.2753	−7.7	−8.0
Houston, Texas	GW 18	29 44.2	95 25.0	59	979.2985	−13.2	−15.2
Rosenberg, Texas	U 730	29 33.5	94 47.5	100	979.2788	−15.2	−18.7
Salt Lake City, Utah	U 49	40 46.1	111 53.8	4,336	979.8038	−37.2	−185.0
Vernal, Utah	U 1175	40 26.9	109 30.8	5,310	979.6686	−52.3	−233.2
Lexington, Va.	U 175	37 47.2	79 26.6	1,063	979.8641	−21.3	−57.6
Bellingham, Wash.	U 220	48 45.1	122 28.6	66	980.8855	−75.5	−77.6
Bremerton, Wash.	U 226	47 34.4	122 37.8	20	980.8117	−47.8	−48.5
Everett, Wash.	U 221	47 58.6	122 12.5	141	980.7807	−103.7	−108.5
Olympia, Wash.	U 112	47 3.4	122 52.7	62	980.8170	+7.9	+5.8
Port Angeles, Wash.	U 223	48 7.0	123 25.9	84	980.8752	−27.2	−30.0
Calgary, Can.	GW 32	51 6.6	114 31.0	3,555	980.8281	−14.6	−135.7
Edmonton, Can.	GW 25	53 31.3	113 31.3	2,197	981.1678	−13.4	−88.3
Fort St. John, Can.	GW 29	56 14.3	120 44.1	2,274	981.4059	+0.9	−76.6
Watson Lake, Can.	GW 8	60 7.8	128 48.1	2,260	981.7141	−7.4	−84.4
Whitehorse, Can.	GW 26	60 42.8	135 3.5	2,281	981.7486	−16.2	−94.0
Mexico City, Mex. (Tacubaya)	GW 41	19 24.3	99 11.7	7,539	977.9419	+33.3	−223.5
Monterrey, Mex.	GW 21	25 38.0	100 17.0	1,860	978.8055	−33.0	−96.4
Paso de Cortes, Mex.	GW 42	19 7.2	98 38.0	13,090	977.5711	+200.6	−245.3
Mexico City, Mex. (University)	GW 43	19 24.3	99 11.7	7,547	977.9414	+33.6	−223.5

TABLE IX. AIRPORTS. COMPARISON OF L&R GEODETIC NO. 1 WITH ADJUSTED 1958 VALUES

	Station	A Unadjusted Woollard (58)	B Geodetic #1	C Adjusted Woollard (58)	Difference C−B
WA 81	Birmingham, Ala.	.5389	.5390	.5392	+.0002
WA 83	Los Angeles, Calif.	.5944	.5946	.5947	+.0001
WA 85	San Diego, Calif.	.5366	.5369	.5369	.0000
WA 86	San Francisco, Calif.	.9880	.9883	.9881	−.0002
WA 89	Denver, Colo.	.6330	.6335	.6333	−.0002
U 337A	Washington, D. C. (Comm. Outside)	.1182	.1182	.1182	.0000
WA 94	Jacksonville, Fla.	.3855	.3856	.3859	+.0003
WA 95	Pensacola Fla.	.3626	.3630	.3630	.0000
WA 97	Atlanta, Ga.	.5203	.5205	.5206	+.0001
WA 99	Savannah, Ga.	.4977	.4980	.4980	.0000
WA 102	Indianapolis, Ind.	.0933	.0933	.0934	+.0001
WA 103	Lafayette, Ind.	.1468	.1469	.1468	−.0001
WA 110	New Orleans, La.	.3294	.3298	.3298	.0000
WA 116	Detroit, Mich.	.3187	.3188	.3187	−.0001
WA 118	Minneapolis, Minn.	.5951	.5950	.5950	.0000
WA 120	Kansas City, Mo.	.9997	.9998	.9998	.0000
WA 123	Butte, Mont.	.1740	.1744	.1740	−.0004
WA 127	Missoula, Mont.	.4438	.4440	.4437	−.0003
WA 128	La Vegas, Nev.	.6047	.6049	.6049	.0000
WA 131	Santa Fe, N. M.	.1970	.1974	.1975	+.0001
WA 132	New York (LaGuardia), N. Y.	.2827	.2825	.2825	.0000
WA 134	Syracuse, N. Y.	.3965	.3968	.3968	.0000
WA 136	Cincinnati, Ohio	.9929	.9931	.9930	−.0001
WA 137	Cleveland, Ohio	.2325	.2322	.2325	+.0003
WA 139	Tulsa, Okla.	.7762	.7766	.7764	−.0002
WA 140	Eugene, Ore.	.5150	.5148	.5149	+.0001
WA 141	Medford, Ore.	.2363	.2375	.2363	(Poss. not the same site)
WA 145	Pittsburgh, Pa.	.0994	.0993	.0995	+.0002
WA 148	Charleston, S. C.	.5664	.5668	.5667	−.0001
WA 152	Brownsville, Texas	.0505	.0509	.0511	+.0002
WA 155	El Paso, Texas	.0811	.0814	.0817	+.0003
WA 162	San Antonio, Texas	.1971	.1975	.1976	+.0001
WA 165	Burlington, Vt.	.5273	.5181	.5272	+.0091
WA 170	Seattle, Wash.	.7769	.7765	.7767	+.0002
WA 173	Spokane, Wash.	.6463	.6463	.6461	−.0002
WA 174	Charleston, W. Va.	.9256	.9259	.9257	−.0002
GW 3	Madison, Wis. (Base)	.3689	.3689	.3689	.0000
WA 176	Milwaukee, Wis.	.3597	.3597	.3597	.0000
WA 177	Casper, Wyo.	.9560	.9562	.9561	−.0001

TABLE X. PRINCIPAL FACTS WOOLLARD 1958 (ADJUSTED) AIRPORT STATIONS

	Station	Lat.	Long.	Elev.	Observed Gravity	Free Air Anomaly	Bouguer Anomaly
WA 1	Muscle Shoals, Ala.	34 45.0	87 37.0	548	979.6914	+18.5	−0.1
WA 2	Phoenix, Ariz.	33 26.0	112 1.1	1,120	979.4918	−17.1	−55.3
WA 3	Tucson, Ariz.	32 7.5	110 57.0	2,595	979.2277	−35.1	−123.6
WA 4	Little Rock, Ark.	34 44.0	92 14.0	260	979.7245	+26.0	+17.1
WA 5	Fresno, Calif.	36 46.5	119 42.5	331	979.8328	−33.6	−44.8
WA 6	Colorado Springs, Colo.	38 48.5	104 42.7	6,172	979.4833	−11.2	−221.5
WA 7	Washington, D. C. (Field level, Nat'l. Apt.)	38 51.1	77 1.8	16	980.1100	+32.6	+32.1
WA 8	Washington, D. C. (Street side, Nat'l. Apt.)	38 51.1	77 1.8	30	980.1090	+33.0	+31.9
WA 9	Daytona Beach, Fla.	29 11.1	81 3.0	34	979.2782	+6.7	+5.5
WA 10	Gainesville, Fla.	29 41.5	82 16.5	155	979.3064	+7.2	+1.9
WA 11	Miami, Fla.	25 47.8	80 17.0	9	979.0540	+29.9	+29.5
WA 12	Ocala, Fla.	29 10.0	82 9.4	84	979.2618	−3.6	−6.5
WA 13	Orlando, Fla.	28 33.0	81 19.4	115	979.2191	+3.6	−0.4
WA 14	Sarasota, Fla.	27 23.4	82 32.9	24	979.1444	+6.8	+6.0

(*Continued on next page*)

TABLE X. (*Continued*)

	Station	Lat.	Long.	Elev.	Observed Gravity	Free Air Anomaly	Bouguer Anomaly
WA 15	St. Petersburg, Fla.	27 54.5	82 41.4	12	979.1974	+20.3	+19.9
WA 16	Tampa, Fla.	27 58.5	82 31.4	26	979.2047	+24.0	+23.1
WA 17	West Palm Beach, Fla.	26 41.2	80 5.5	15	979.1332	+46.1	+45.6
WA 18	Brunswick, Ga.	31 11.4	81 29.4	14	979.4498	+19.4	+19.0
WA 19	Columbus, Ga.	32 30.5	84 56.6	397	979.5125	+11.7	−1.9
WA 20	Macon, Ga.	32 42.0	83 38.5	354	979.5323	+11.8	−0.3
WA 21	Boise, Idaho	43 34.0	116 13.4	2,858	980.2082	−23.0	−120.4
WA 22	Chicago, Ill.	41 59.6	87 54.0	666	980.2894	−6.5	−29.2
WA 23	Springfield, Ill.	39 45.1	89 41.6	606	980.0821	−19.3	−40.0
WA 24	Cedar Rapids, Iowa	41 53.5	91 43.3	863	980.2519	−16.3	−45.7
WA 25	Des Moines, Iowa	41 31.8	93 38.8	957	980.1984	−28.6	−61.2
WA 26	Louisville, Ky.	38 11.1	85 44.4	497	979.9586	−14.9	−31.9
WA 27	Shreveport, La.	32 32.5	93 44.8	179	979.5305	+6.5	+0.4
WA 28	Mankato, Minn.	44 8.9	93 58.6	1,005	980.4666	+8.6	−25.6
WA 29	Rochester, Minn.	44 0.0	92 27.0	1,041	980.4311	−10.1	−45.6
WA 30	Jackson, Miss.	32 20.1	90 13.4	343	979.5270	+35.3	+23.6
WA 31	Helena, Mont.	46 36.5	111 59.5	3,882	980.3778	−31.6	−163.8
WA 32	Kalispell, Mont.	48 18.8	114 15.8	2,971	980.5818	−66.7	−167.9
WA 33	Alliance, Neb.	42 3.2	102 48.7	3,930	980.0105	+16.2	−117.6
WA 34	Grande Island, Neb.	40 58.1	98 18.5	1,846	980.0957	+2.6	−60.3
WA 35	Lincoln, Neb.	40 51.5	96 46.2	1,191	980.1756	+30.7	−9.9
WA 36	North Platte, Neb.	41 8.5	100 42.0	2,779	980.0295	+8.7	−86.0
WA 37	Omaha, Neb.	41 18.0	95 53.5	982	980.2143	+10.3	−23.2
WA 38	Scotts Bluff, Neb.	41 52.2	103 36.2	3,965	979.9482	−26.3	−161.4
WA 39	Ely, Nev.	39 17.8	114 50.8	6,258	979.4946	−34.9	−248.1
WA 40	Tonopah, Nev.	38 3.5	117 5.2	5,426	979.4767	−22.1	−207.0
WA 41	Lebanon, N. H.	43 38.0	72 18.6	579	980.4412	−10.4	−30.1
WA 42	Wrightstown, N. J.	40 1.6	74 35.8	120	980.2127	+41.1	+37.1
WA 43	Alamogordo, N. M.	32 51.5	106 6.0	4,092	979.1484	−33.5	−172.9
WA 44	Charlotte, N. C.	35 12.8	80 56.2	748	979.7283	+35.0	+9.5
WA 45	Greensboro, N. C.	36 5.6	79 56.0	913	979.7658	+12.9	−18.2
WA 46	New Bern, N. C.	35 4.9	77 2.5	18	979.7286	−22.2	−22.8
WA 47	Raleigh Durham, N. C.	35 52.2	78 47.0	435	979.8018	+23.1	+8.3
WA 48	Wilmington, N. C.	34 16.6	77 54.6	31	979.6772	−4.5	−5.5
WA 49	Bismarck, N. D.	46 46.8	100 45.5	1,653	980.6274	−7.1	−63.4
WA 50	Fargo, N. D.	46 54.9	96 48.9	900	980.7270	+9.5	−21.2
WA 51	Jamestown, N. D.	46 56.0	98 41.0	1,498	980.6540	−8.9	−59.9
WA 52	Columbus, Ohio (Old terminal)	40 00.0	82 52.2	830	980.0774	−25.0	−53.3
WA 53	McAlester, Okla.	34 55.0	95 45.2	750	979.6274	−40.5	−66.1
WA 54	Oklahoma City, Okla.	35 23.5	97 36.9	1,283	979.6656	+7.5	−36.2
WA 55	Pendleton, Ore.	45 41.5	118 50.4	1,493	980.5117	−39.7	−90.6
WA 56	Salem, Ore.	44 54.7	123 0.0	207	980.5837	−18.2	−25.3
WA 57	Florence, S. C.	34 11.4	79 43.9	146	979.6851	+21.5	+16.6
WA 58	Greenville, S. C.	34 51.0	82 21.0	1,049	979.6232	−11.0	−46.7
WA 59	Aberdeen, S. D.	45 27.3	98 26.0	1,300	980.5438	−4.4	−48.7
WA 60	Brookings, S. D.	44 18.1	96 48.6	1,626	980.4302	+16.8	−38.6
WA 61	Hot Springs, S. D.	43 21.5	103 24.8	3,075	980.1954	+3.3	−101.4
WA 62	Huron, S. D.	44 23.0	98 13.3	1,287	980.4527	0.0	−43.8
WA 63	Rapid City, S. D.	44 3.0	103 3.6	3,172	980.2510	+5.7	−102.4
WA 64	Spearfish, S. D.	44 28.7	103 47.1	3,929	980.2521	+39.4	−94.5
WA 65	Memphis, Tenn.	35 3.5	89 58.9	291	979.7257	+2.6	−7.3
WA 66	Nashville, Tenn.	36 7.0	86 41.0	606	979.7796	−4.2	−24.8
WA 67	Amarillo, Texas	35 13.8	101 42.0	3,604	979.4234	−2.7	−125.4
WA 68	Lubbock, Texas	33 39.3	101 48.9	3,256	979.3228	−3.6	−114.5
WA 69	Tyler, Texas	32 21.0	95 24.1	544	979.4782	+4.1	−14.4
WA 70	Wichita Falls, Texas	33 59.0	98 30.5	1,029	979.5483	−14.9	−50.0
WA 71	Ogden, Utah	41 12.2	112 0.9	4,455	979.8178	−50.9	−202.7
WA 72	Montpelier, Vt.	44 12.5	72 34.1	1,100	980.4629	+8.4	−29.0
WA 73	Richmond, Va.	37 30.5	77 19.2	167	979.9534	+7.9	+2.2
WA 74	Walla Walla, Wash.	46 5.9	118 17.0	1,205	980.5740	−41.2	−82.2
WA 75	LaCrosse, Wis.	43 53.0	91 16.0	653	980.4567	−10.5	−32.7
WA 76	Madison, Wis.	43 8.7	89 20.0	859	980.3725	−8.8	−38.0
WA 77	Montreal, Que., Can.	45 27.0	73 45.0	103	980.6439	−16.4	−19.9
WA 78	Ottawa, Ont., Can.	45 20.1	75 41.2	357	980.6215	−4.5	−16.7
WA 79	Toronto, Ont., Can.	43 41.5	79 38.1	557	980.4298	−29.1	−48.1
WA 80	Winnipeg, Manitoba, Can.	49 54.2	97 14.5	775	980.9924	−4.7	−31.1

TABLE XI. COMPARISON L&R GEODETIC NO. 1 VS. USC&GS PENDULUM VALUES

Station		A L&R Geodetic #1	B USC&GS	B−A ΔG
Tuscaloosa, Ala.	U 1119	979.5598 gals.	.562 gals.	+2.2 mgals.
Eureka, Calif.	U 238	980.2219	.223	+1.1
Oceanside, Calif.	U 241	979.5663	.571	+4.7
Santa Rosa, Calif.	U 239	980.0203	.024	+3.7
Colorado Springs, Colo.	U 1078	979.4931	.494	+0.9
Craig, Colo.	U 1164	979.6202	.622	+1.8
Dept. of Commerce, D. C.	U 337A	980.1182	.1176	−0.6
Crestview, Fla.	U 890	979.3815	.377	−4.5
Lake City, Fla.	U 869	979.3340	.334	0.0
Mariana, Fla.	U 399	979.3665	.367	+0.5
Pensacola, Fla.	U 164	979.3631	.363	−0.1
Atlanta, Ga.	U 15	979.5238	.527	+3.2
Chicago, Ill.	U 36	980.2858	.281	−4.8
Indianapolis, Ind.	U 137	980.0898	.093	+3.2
Baltimore, Md.	U 23A	980.1164	.114	−2.4
Boston, Mass.	U 29	980.3967	.399	+2.3
Cambridge, Mass.	U 30	980.4011	.401	−0.1
Laurel, Miss.	U 145	979.4697	.468	−1.7
Forsyth, Mont.	U 584	980.5089	.514	+5.1
Albuquerque, N. M.	U 764	979.2232	.221	−2.2
Wilmington, N. C.	U 149	979.6703	.668	−2.3
Columbus, Ohio	U 136	980.0864	.092	+5.6
Eugene, Ore.	U 232	980.4910	.493	+2.0
Portland, Ore.	U 229	980.6474	.649	+1.6
Philadelphia, Pa.	U 957	980.1974	.197	−0.4
Charleston, S. C.	U 17	979.5501	.549	−1.1
Cleveland, Tenn.	U 153	979.6517	.652	+0.3
Alpine, Texas	U 98	978.9910	.994	+3.0
Corpus Christi, Texas	U 727	979.1489	.145	−3.9
Del Rio, Texas	U 723	979.1920	.193	+1.0
Denison, Texas	U 73A	979.5712	.569	−2.2
El Paso, Texas	U 63	979.1257	.127	+1.3
Galveston, Texas	U 7	979.2753	.276	+0.7
Rosenberg, Texas	U 730	979.2788	.279	+0.2
Salt Lake City, Utah	U 49	979.8038	.806	+2.2
Vernal, Utah	U 1175	979.6686	.671	+2.4
Lexington, Va.	U 175	979.8641	.862	−2.1
Bellingham, Wash.	U 220	980.8855	.887	+1.5
Bremerton, Wash.	U 226	980.8117	.813	+1.3
Everett, Wash.	U 221	980.7807	.784	+3.3
Olympia, Wash.	U 112	980.8170	.828	+11.0
Port Angeles, Wash.	U 223	980.8752	.878	+2.8
Madison, Wis.	U 37	980.3689	.368	−0.9

between Tables XII and XIII is striking and substantiates the earlier conclusion that there are datum shifts associated with periods of operation.

TABLE XII. AVERAGE ERROR USC&GS PENDULUM STATIONS IN MIDWEST AREA

Year of Pendulum Work	No. of Observations	Average Deviation Rel. Gravimeter
1890–1930	11	+2.3 mgals
1932	5	−3.5
1934	6	+3.3
1936–1939	5	−0.3
1940–1941	5	+0.1
1948	4	+2.1

Part of the change noted can be correlated with change in instrumentation. From 1891 to 1920 the pendulums used were of aluminum-bronze material and a flash apparatus was used for determining the coincidence of the pendulum beats and chronometer ticks. In 1921 invar pendulums were

TABLE XIII

Year of Pendulum Work	No. of Observations	Average Deviation Rel. Gravimeter
1890–1930	26	+2.5 mgals
1936–1939	13	−0.6
1948	3	+2.8

adopted and radio time signals replaced star observations in determining the pendulum period. In 1931 another change was made in instrument design and it is coincidental with this change in apparatus design that the apparent shifts in datum with operational field season becomes apparent.

CONCLUSION

The present study not only furnishes reliable control to 0.1 mgal for future gravity studies and adjustment of old gravity surveys to a common datum and calibration standard, but also makes it possible through anomaly comparisons to effectively adjust old gravity surveys for which the original data are not available or have been misplaced or lost.

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The writers are indebted to many individuals too numerous to mention for their assistance in carrying out the program, but do wish to mention the assistance of Monroe Woollard and Jan Black who took part in carrying out the measurements. The work was supported under a grant from the National Science Foundation.

REFERENCES

Duerksen, J. A., 1949, Pendulum gravity data in the United States: U. S. Coast and Geodetic Survey. Spec. Pub. 244, 218 pp.

Ferris, Craig, 1943, Use of the gravity meter in establishment of gravity bench marks: Geophysics v. 8, n. 4.

Woollard, G. P., 1950, The gravity meter as a geodetic instrument: Geophysics, v. 15, n. 1.

———, 1958, Results for a gravity control network at airports in the United States: Geophysics, v. 23, n. 3, p. 520–535.

———, Harding, N. C., and Rose, J. C., 1955, The problem of calibrating high-range geodetic type gravimeters: Trans. Am. Geophys. Un., v. 36, n. 1, p. 12–24.

———, Rose, J. C., and Bonini, W. E., 1956, The establishment of an international gravity standard: Trans. Am. Geophys. Un., v. 37, n. 2, p. 143–155.

APPENDIX

Table I. Results on North American Standardization Range.

Table II. Gravity Results at Main Control Stations.

Table III. L and R Geodetic No. 1 Airport Gravity Base Stations.

Table IV. University Gravity Base Stations.

Table V. Gravimeter Occupations of Pendulum Stations.

Table VI. Harbor Gravity Base Stations.

Table VII. L and R Geodetic No. 1 Airport Stations.

Table VIII. Principal Facts Pendulum Stations (Reoccupied).

Table IX. Comparison of L and R Geodetic No. 1 with Adjusted 1958 Values.

Table X. Principal Facts Woollard 1958 (Adjusted) Airport Stations.

Table XI. Comparison L and R Geodetic No. 1 vs. USC and GS Pendulum Values.

Note: In the above tables the station numbering system used is as follows:

U series: Sites originally occupied by the U. S. Coast and Geodetic Survey with single pendulum apparatus.

GW series: Sites originally occupied by the University of Wisconsin with the compound quartz pendulum apparatus developed by the Gulf Research and Development Company.

C series: Sites originally occupied by the Lamont Geological Observatory of Columbia University with the compound submarine pendulum apparatus developed by F. Vening Meinesz.

WA series: Airport sites occupied by the University of Wisconsin with gravimeters.

WH series: Harbor sites occupied by the University of Wisconsin with gravimeters.

WU series: University and other institutional sites occupied by the University of Wisconsin with gravimeters.

GEOPHYSICS, VOL. XXVI, NO. 1 (FEBRUARY, 1961), PP. 77–84, 5 FIGS.

EFFECT OF POROSITY, GRAIN CONTACTS, AND CEMENT ON COMPRESSIONAL WAVE VELOCITY THROUGH SYNTHETIC SANDSTONES*

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Abstract: Compressional wave velocities through 36 synthetic sandstone cores were measured and related to several of their physical properties, namely, porosity, manufacturing pressure, grain contacts, and amount of cement. The cores were composed of Ottawa sand grains averaging 0.21 mm in diameter and commercial Grefco cement; the manufacturing pressure was varied from 4,000 to 10,000 psi; the cement content by volume was varied from 10 to 100 percent; the effective porosities ranged between 2.1 and 30.4 percent; and the compressional wave velocities ranged between 9,170 and 17,420 ft/sec. All velocity measurements were taken at room temperature and atmospheric pressure using cores that contained only air in the pore space.

The results are presented in graphic form, showing the relationship between the compressional wave velocity and manufacturing pressure, porosity, and cement content. For Grefco cement contents between 10.0 and 17.5 percent, the compressional wave velocity is controlled by the manufacturing pressure and the porosity. A change in manufacturing pressure of 1,000 psi changed the compressional wave velocity by one percent for cores having porosities of about 23 percent and by about 3 percent for cores having porosities of about 28 percent. A decrease in porosity of one percent increased the velocity by an average of 1.4 percent for effective porosities between 23 and 26 percent. The velocity is also dependent, to a great extent, on the number of grain contacts which is intimately associated with the manufacturing pressure, and the cement content which is intimately associated with the porosity. For cement contents greater than 17.5 percent by volume, the sand grains float in the cement, and the analogy between the synthetic sandstone cores and natural sandstones is questionable.

INTRODUCTION

The object of this research was to isolate some of the physical properties of synthetic sandstone cores and to determine their relative importance in controlling the compressional wave velocity through the cores. Neglecting the fluid in the pore space and the temperature of the frame, the major factors that control the compressional wave velocity through sandstone are thought to be the porosity, the pressure on the frame, the grain contacts, the amount and type of cement, and the grain size. Many of these variables cannot be considered as independent, and the first and second order effects can be differentiated mainly through experimentation.

Murphy et al (1957) conducted compressional wave velocity studies using synthetic sandstone cores composed of sand grains and commercial cements. In this study, the propagational velocity of elastic waves through the cores was studied as a function of the porosity and the propagational velocity of compressional waves through the fluid filling the pore space. From experimental results, it was concluded that the velocity through the cores was dependent upon the porosity and the type of fluid in the cores, and that the type and amount of cement apparently had some effect on the propagational velocity of the elastic waves through the cores.

Previous work has been done on interrelating the depth of burial of sandstones, compaction, porosity, and grain contacts. Taylor (1950) correlated the depth of burial of sandstones with the number and type of grain contacts (i.e., tangential, long, concave, and convex), and showed that an average linear relationship exists between the depth of burial and the number of contacts per grain. It was shown by Gaither (1953) than an artificial sandstone composed of sand and

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Lakeside 70 cement had undergone compaction if it had a porosity of about 37 percent or less, an average number of contacts per grain in excess of 0.85, floating grains less than 46 percent, and grains with four or more contacts present. Floating grains represent grains that are completely surrounded by cement.

Hughes and Jones (1950) found that in igneous rocks the increase of propagational velocity of elastic waves with an increase in pressure was much greater at low pressures than at high pressures, where the rate of increase becomes essentially linear. They believed that the initial increase in velocity is due mostly to the closing of the pore space.

EXPERIMENTAL METHODS

The instrumentation used in this investigation is the same as that used by Murphy et al (1957). Throughout the investigation, only the first arrival was used which represented the direct compressional wave through the core. The travel time through an aluminum cylinder was employed as a standard before any measurements were taken. Five measurements of velocity were made and averaged for each core to obtain the final velocity. All measurements of velocity were made using dry cores at room temperature and atmospheric pressure. Porosities were determined by standard vacuum techniques, and all porosities referred to in this paper are effective porosities.

In the manufacturing of the synthetic cores, a method was followed as described by Mandel and others (1957). A single type of cement was used which is commercially known as Grefco and consists of calcium and aluminum oxides in a one-to-one ratio. The quartz sand grains used came from the Ottawa sandstone, and as observed under a microscope, ranged from 0.10 mm to 0.45 mm in diameter, with an average diameter of 0.21 mm. The grains are rather uniform in size and shape, and their dimensions are well within the range of those of natural sandstones.

Cores were made containing 10.0, 12.5, 15.0, 17.5, 20.0, 40.0, 60.0, 80.0, and 100.0 percent cement by volume, respectively; all cement contents referred to in this paper are cement contents by volume. Manufacturing pressures of 4,000, 6,000, 8,000, and 10,000 psi were used during the manufacture of the cores. The term "manufacturing pressure," as used here, indicates the maximum pressure to which the wet sand-cement mixture was subjected during the manufacture of the cores. After this amount of pressure had been applied for about five minutes, the core was taken out of the core barrel and allowed to harden for about 24 hours at atmospheric pressure in an oven at about 95 degrees C. The dried core was then weighed, flooded with distilled water, and dried in the oven again. The entire procedure was repeated until the core came to within a few milligrams of a constant weight.

For each percentage of cement, at least one core was made for each of the four different manufacturing pressures. Thus a total of more than 36 cores were made and used in this work.

An attempt was made to manufacture cores below a pressure of 4,000 psi, but the cores were friable and no permanent cores could be obtained. The effective porosities of the synthetic cores ranged from 2.1 to 30.4 percent. The effective porosity includes both the interstitial porosity and the porosity of the cement itself. Above a cement content of approximately 17.5 percent, it is rarely possible for individual grains to touch even at one point because of the large amount of cement present, and hence they are mostly floating grains.

EXPERIMENTAL RESULTS

The propagational velocities of the compressional waves through the synthetic cores ranged between 9,170 and 17,420 ft/sec, when the manufacturing pressure varied from 4,000 to 10,000 psi and the cement content by volume varied from 10 to 100 percent, respectively.

Figure 1 shows the plot of the velocity versus the manufacturing pressure for the total cement content range of 10 to 100 percent. The graph shows that after a certain increase in manufacturing pressure, the velocities apparently tend toward limiting values. The curves representing large cement contents tend toward high limiting velocities. This observation indicates that the cement content is an important consideration at all manufacturing pressures. For cement contents of 17.5 percent or less, the close spacing of the curves in Figure 1 indicates that the apparent limiting values of velocity are probably influenced by the bridging effects of the sand grains (grain-to-grain contacts). The wide spacing of the curves for 17.5 and 20.0 percent cement content

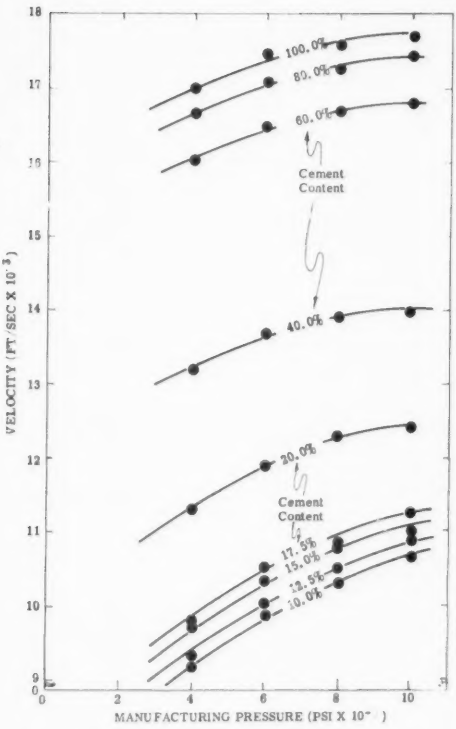

FIG. 1. Compressional wave velocity versus manufacturing pressure for synthetic sandstone cores with different cement contents by volume.

by volume, indicates a transitional zone in which the effect of the cement is more predominant at 20.0 percent than at 17.5 percent in controlling the velocity. Murphy et al (1957) showed that some of the sand grains of a synthetic core were floating when the core contained 20 percent or more cement by volume. It is believed therefore that the wide spacing of the curves between 17.5 and 20.0 percent cement in Figure 1 indicates that the sand grains start floating at approximately 17.5 percent cement by volume. Although in this paper data are presented for cement contents above 17.5 percent by volume, the analyses of the data, in terms of the effects of porosity and manufacturing pressure on compressional wave velocity, are restricted to cores containing 17.5 percent cement by volume and less. For cement contents by volume greater than 17.5 percent, the analogy between such synthetic sandstone cores and natural sandstones is questionable.[1] For all cement contents at any given manufacturing pressure, the curves in Figure 1 indicate that the frame of the core with a cement-sand mixture has continuously lower velocities for increasing amounts of sand, and hence has lower values of elastic constants than the pure cement.

Figure 2 shows a series of plots of the velocity versus the effective porosity in percent at constant cement contents. The data used for plotting these graphs are identical to that used for plotting Figure 1. For graphs A, B, C, and D, the porosity range is between about 20 and 30 percent, and the cement contents of the cores are 10.0, 12.5, 15.0, and 17.5 percent, respectively. For these four graphs, the velocity appears to increase linearly with a decrease in porosity; the approximation by a straight line shown for each of these four graphs is drawn by the least square method through the points. For the assumed linear relationships shown on Figures 2A, 2B, 2C, and 2D, the magnitudes of the slopes of these lines are 270 ft/sec, 360 ft/sec, 306 ft/sec, and 332 ft/sec per one percent change in porosity for the four cores containing 10.0, 12.5, 15.0, and 17.5 percent cement, respectively. If a velocity of 10,000 ft/sec is assumed to be the average for all graphs, the changes in velocity for a one percent change in porosity are 2.7, 3.6, 3.1, and 3.3 percent for the above respective percentages of cement. These results show that in the porosity range between about 20 and 30 percent, the velocity increases approximately 3 percent for a one percent decrease in porosity, provided the changes in manufacturing pressure are neglected. The above slopes vary by less than one percent change in velocity per one percent change in porosity when the cement content varies between 10.0 and 17.5 percent.

For the remaining plots in Figure 2, the sand grains are floating in the cement, and no detailed analysis was made of these data.

In Figure 3, the velocity is plotted versus the manufacturing pressure at constant values of effective porosity of 23, 24, 26, and 28 percent, re-

[1] There exists a difference in the type of grain contacts between the synthetic cores used in this research and natural sandstones. In the synthetic cores, the grains may not really touch each other as there exists a film of cement that coats each grain. In most natural sandstones, no such cement coating exists; rather the cement is present in the interstitial space only.

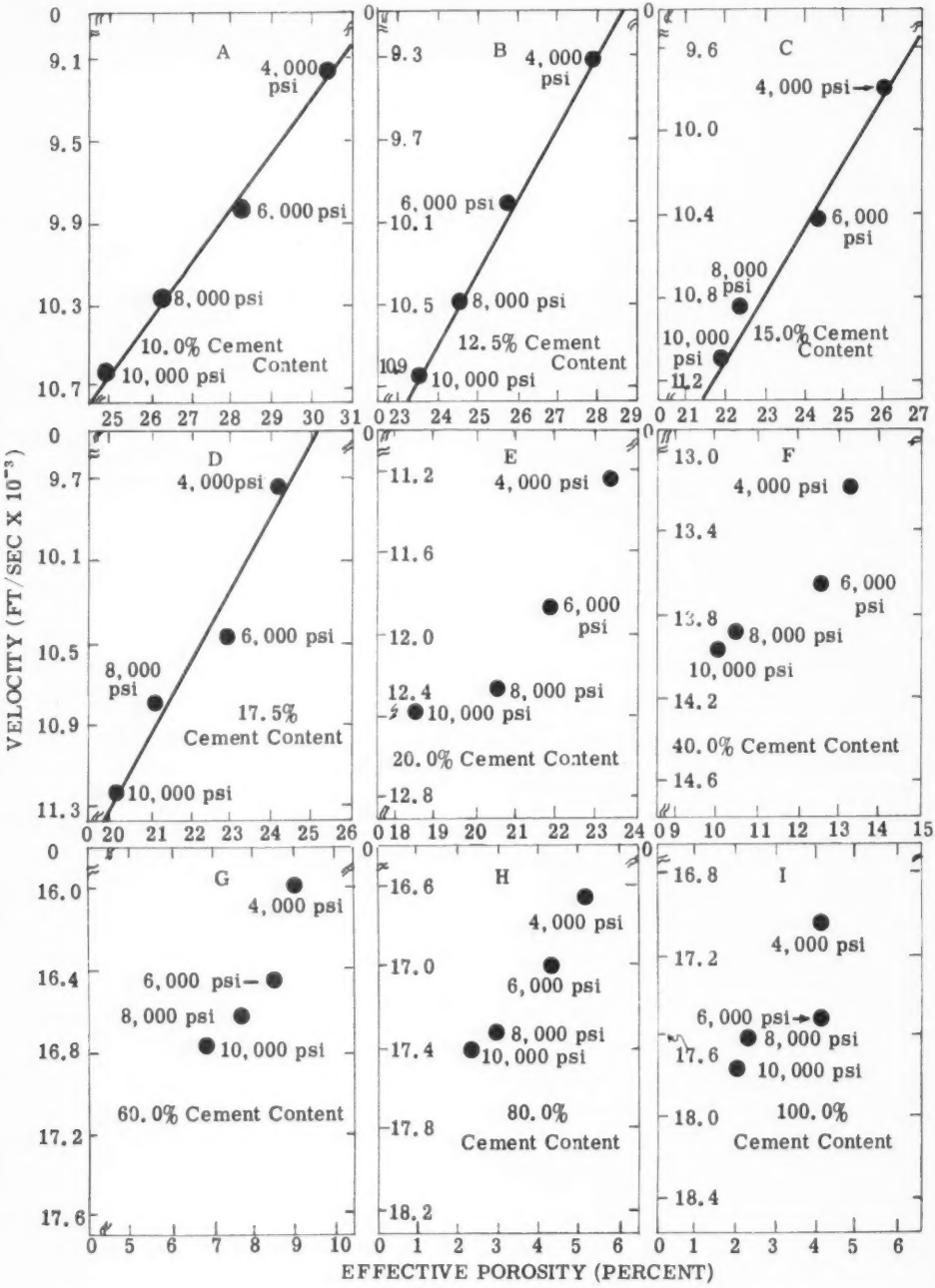

FIG. 2. Compressional wave velocity versus effective porosity for synthetic sandstone cores at constant cement content by volume and with manufacturing pressures varying from 4,000 to 10,000 psi.

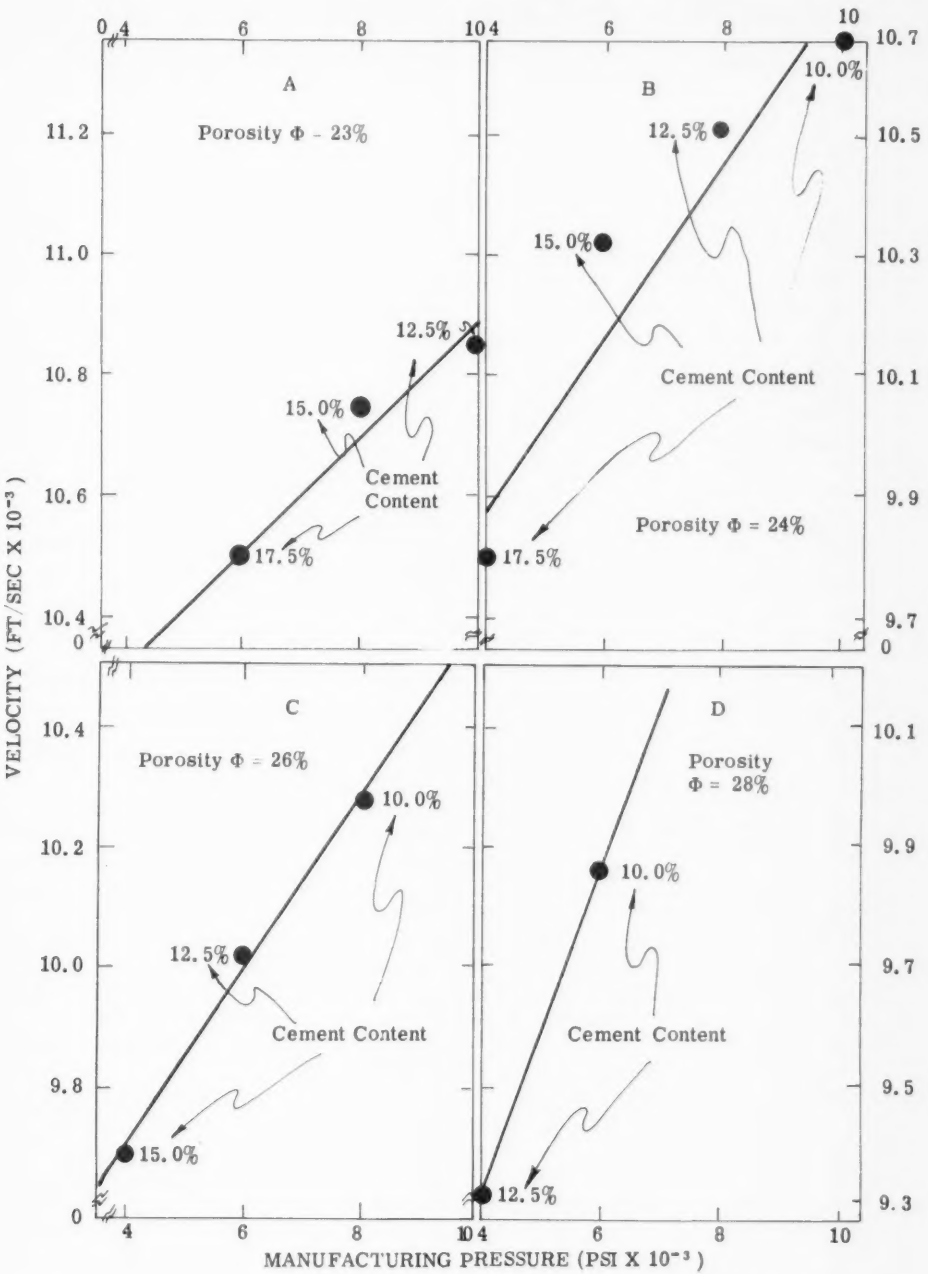

FIG. 3. Compressional wave velocity versus manufacturing pressure for synthetic sandstone cores at constant effective porosities of 23, 24, 26, and 28 percent, respectively.

spectively, for cement contents of 17.5 percent or less. Cores of the same porosity have been grouped together. Each of the four plots shows that the velocity increases nearly linearly with an increase of manufacturing pressure, even though the cement content decreases. Thus, this observation indicates that, for cement contents between 10.0 and 17.5 percent, the amount of Grefco cement has less influence on the velocity than the manufacturing pressure. Assuming the linear relationships shown on graphs A, B, C, and D in Figure 3 for the purpose of the following analysis, the reciprocal slopes for the lines shown on these graphs are 185 ft/sec, 272 ft/sec, 300 ft/sec, and 540 ft/sec for a manufacturing pressure differential of 2,000 psi at porosities of 23, 24, 26, and 28 percent, respectively. Assuming a velocity of 10,000 ft/sec to be average for all graphs and normalizing with respect to a pressure differential of 1,000 psi, it is calculated that an increase of manufacturing pressure of 1,000 psi increases the velocities by 0.9, 1.4, 1.5, and 2.7 percent at porosities of 23, 24, 26, and 28 percent, respectively. It should be noted that for corresponding changes in the manufacturing pressure, the velocity is increased three times as much at the higher porosities than at the lower porosities.

To obtain the way in which the velocity varies as a function of porosity, the graphs of Figures 2 and 3 were compared. As an example, on graph C of Figure 2 the velocity varies from about 10,900 ft/sec at 22.8 percent porosity to 10,400 ft/sec at 24.2 percent porosity. On this same graph and for these values, the manufacturing pressure varies from 8,000 to 6,000 psi. Thus, the porosity variation and the manufacturing pressure variation combine to cause a variation of 500 ft/sec in velocity. On graph A of Figure 3 for a porosity of 23 percent, a manufacturing pressure of 8,000 psi on the abscissa corresponds to a velocity of 10,750 ft/sec on the ordinate, and a pressure of 6,000 psi on the abscissa corresponds to a velocity of 10,500 ft/sec on the ordinate. Thus, from Figure 3 a pressure differential of 2,000 psi causes a 250 ft/sec variation in velocity for a core of 23 percent porosity. If this effect of manufacturing pressure variation is subtracted from the data obtained from graph C of Figure 2, the porosity variation of 1.4 percent results in a net velocity variation of 250 ft/sec. Normalizing with respect to a one percent porosity and a velocity of 10,000 ft/sec, the velocity is calculated to increase by 1.8 percent for a one percent decrease in porosity for cores having approximately 23 percent porosity. Similarly, using graph B on Figure 2 and graph C on Figure 3, the velocity is calculated to increase by 1.5 percent for a one percent decrease in porosity for cores having approximately 26 percent porosity. Using graph B on Figure 2 and graph B on Figure 3, the velocity is calculated to increase by 1.0 percent for a one percent decrease in porosity. For this calculation, the pressure range was between 8,000 and 10,000 psi. By this method of analysis the above calculations show that the velocity increases by an average of approximately 1.4 percent for a porosity decrease of one percent, for the synthetic cores having effective porosities between 23 and 26 percent.

A study of the thin sections in conjunction with the graphic data of this investigation suggests that the increase in velocity with an increase in manufacturing pressure is caused by the concurrent increase in the number of grain contacts and the compaction of the cement. For a cement content of 15 percent by volume, the average number of grain contacts increased from values of 0.5 to 1.0 per grain at a manufacturing pressure of 4,000 psi to values of 2 to 3 per grain at a manufacturing pressure of 10,000 psi. The increase in the average number of grain contacts would make the core more elastic, and an increase in velocity would be expected. However, it should be remembered that in any synthetic sandstone the grains are forced into closer contact by an increase in the manufacturing pressure. Therefore, the effects of the number of grain contacts and of the manufacturing pressure cannot be separated and must be treated as a combined effect.

Figure 4 shows the plot of the velocity versus the cement content for synthetic cores manufactured at a manufacturing pressure of 10,000 psi. For cement contents between 10.0 and 17.5 percent, the velocity apparently increases linearly with increasing cement content. It is noted that a definite change takes place in the propagational velocity—and hence the elastic properties of the core—for cement contents between 17.5 and 20.0 percent. In this cement content range, the thin sections show that the grains start floating in the cement (Murphy et al, 1957, p. 814). For cement contents greater than 20.0 per-

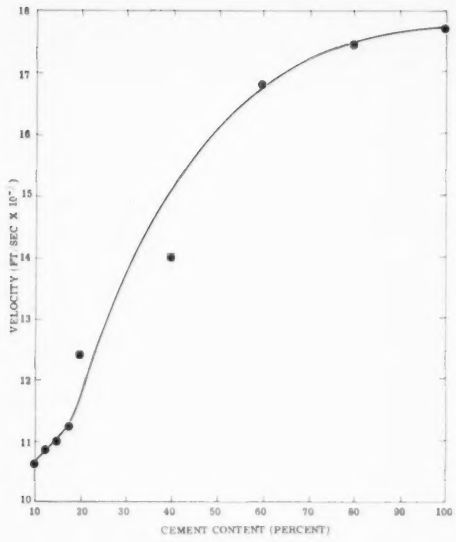

FIG. 4. Compressional wave velocity versus cement content by volume for synthetic sandstone cores at a manufacturing pressure of 10,000 psi.

cent, the velocity apparently increases non-linearly as the cement content increases.

Figure 5 shows the plot of velocity versus the cement content obtained using synthetic cores with Grefco cement at manufacturing pressures of 4,000 and 10,000 psi. The cement content varies from 10.0 to 17.5 percent. It will be noted that if the average variation of velocity (namely 250 ft/sec) with change in porosity of 1.4 percent (see page 82) is considered for these data, porosity effects would account for the entire variation of velocity with cement content shown on Figure 5.

When increased amounts of this cement are used to manufacture cores, it affects the porosity mainly by filling the pore space with a high velocity material and concurrently strengthening the core which increases the velocity through the core. The fact that the effect of variations in cement content and porosity are interdependent is particularly evident on Figure 5. Also, the effects of variations in cement content (and the concurrent variations in porosity) on the velocity differ from the effects of variations in manufacturing pressure and porosity (see Figure 2) on the velocity because an increase in the manufacturing pressure affects the core in two ways: (1) it changes the relative positions of the grains and affects the grain contacts, and (2) it squeezes cement into the pore space of the core. Provided different pressures do not produce different qualities of cement, it would be expected that the effect of (2) as calculated from Figures 2 and 3 (see page 82) would be nearly equivalent to the effect of cement content on velocity as shown on Figure 5. If this filling of the void space with cement is considered as primarily responsible for the decrease in porosity—note that (1) can slightly change the porosity also—the velocity increases by an average of 1.4 percent and 0.9 percent for a one-percent decrease in porosity as computed from Figures 2 and 3 and Figure 5, respectively. These differences are within experimental error and additional refinements are not considered. Thus, it would seem reasonable to conclude that, for these experimental conditions, a decrease in porosity of 1 percent (for porosities between 23 and 28 per-

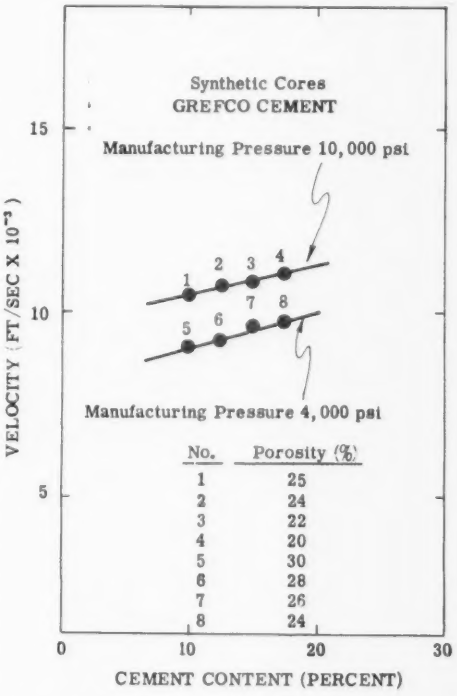

FIG. 5. Compressional wave velocities versus cement content by volume for synthetic sandstone cores with Grefco cement.

cent) increases the velocity by approximately 1 to 2 percent. Further, when cements having different properties cause variations in porosity, the concordant variations in velocities are dependent on the cements that are used (see Murphy et al Figure 2).

CONCLUSIONS

For synthetic sandstone cores containing between 10.0 and 17.5 percent of Grefco cement by frame volume and within the limits of these experiments and analyses, it has been established in this investigation that the compressional wave velocity is controlled by the manufacturing pressure and the porosity. A change in manufacturing pressure of 1,000 psi changed the compressional wave velocity by one percent for cores having porosities of about 23 percent and by three percent for cores having porosities of about 28 percent. A decrease in porosity of one percent increased the velocity by an average of 1.4 percent for porosities between 23 and 26 percent.

The graphical data and the thin sections of the synthetic cores indicate that a transitional stage in the cores occurs for cement contents of 17.5 and 20.0 percent. At this critical stage, and as the amount of the cement increases, the grains start floating in the cement and the elastic constants of the rocks become increasingly dependent on the characteristics of the cement.

For the synthetic cores used in this research containing 17.5 percent cement content or less, the velocity is dependent, to a great extent, on the number of grain-to-grain contacts which is intimately associated with the manufacturing pressure.

ACKNOWLEDGMENTS

The authors extend their appreciation to Professor D. J. Jones, Department of Geology, University of Utah, for offering helpful suggestions. Part of the equipment used for this research was obtained through a grant-in-aid from the Magnolia Petroleum Company. Some of the funds for this research were provided by the American Petroleum Institute Grant-in-aid No. 33.

REFERENCES

Gaither, A., 1953, A study of porosity and grain relationships in experimental sands: Jour. Sed. Petrography, v. 23, no. 31, p. 180–195.

Griffiths, J. C., 1952, Grain size distribution and reservoir rock characteristics: AAPG Bull., v. 36, no. 2, p. 205–229.

Hughes, D. S., and Jones, J. J., 1950, Variation of elastic moduli of igneous rocks with pressure and temperatures: Geol. Soc. America Bull., v. 61, p. 843–856.

———, and Cross, J. J., 1951, Elastic wave velocities at high pressures and temperatures: Geophysics, v. 16, no. 3, p. 577–593.

———, and Kelly, J. T., 1952, Variation of elastic wave velocity with saturation in sandstones: Geophysics, v. 17, no. 4, p. 739–752.

Mandel, Peter, Jr., Berg, J. W., Jr., and Cook, K. L., 1957, Resistivity studies of synthetic metalliferous cores: Geophysics, v. 22, no. 2, p. 398–411.

Murphy, W. O., Jr., Berg, J. W., Jr., and Cook, K. L., 1957, Seismic velocity studies of synthetic sandstone cores: Geophysics, v. 22, no. 4, p. 813–820.

Paterson, N. R., 1956, Seismic wave propagation in porous granular media: Geophysics, v. 21, no. 3, 691–741.

Taylor, J. M., 1950, Pore space reduction in sandstones: AAPG Bull., v. 23, no. 4, p. 701–717.

Waldschmidt, W. A., 1941, Cementing materials in sandstones and their probable influence on migration and accumulation of oil and gas: AAPG Bull., v. 25, p. 1839–1879.

Weller, J. M., 1959, Compaction of sediments: AAPG Bull., v. 43, no. 2, p. 273–310.

Wyllie, M. R. J., Gregory, A. R., and Gardner, L. W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics, v. 21, no. 1, p. 41–70.

REVIEW ARTICLES

The present editorial staff has recognized during its first year of operation that a practical difficulty exists in accepting manuscripts for publication. There exists on the one hand the requirement that manuscripts present something new. This is an obvious requirement to prevent the repetition of material. On the other hand, there is recognized a demand for subject matter which would be useful to our student members and to many of our associate members, subject matter which is not new but which, nevertheless, does not appear in textbooks or in other good collated form.

A pertinent name for this group of subject matter would be "Review Articles." Excellent articles of this type have appeared from time to time in GEOPHYSICS, a recent one being "A Review of Geophysical Instrumentation," by W. T. Born (GEOPHYSICS, Vol. XXV, p. 77, 1960).

The editorial staff, therefore, is initiating with this volume a special section under the heading "Review Articles," in which will appear from time to time articles which are not appropriate to the main body of GEOPHYSICS. Moreover, a prime reason for this separate identification is the anticipation of the day when these articles can be grouped into a special volume entitled "Review Articles from GEOPHYSICS."

The Editor

ANOMALOUS EVENTS ON THE REFLECTION SEISMOGRAM*

DAVID S. SEABROOKE†

Abstract: Anomalous events, i.e., events other than simple reflections, are becoming more and more evident with the advent of magnetic tape and the various types of display sections such as variable area, variable density, full trace, etc. Recognition of these events, such as multiple reflections, diffractions, etc., is of considerable importance if the interpreter is to make optimum use of his data. A knowledge of the characteristics of the anomalous events likely to be encountered aids in their identification. Simple parameters, viz., arrival time, apparent dip stepout and normal moveout, readily obtained from the reflection seismogram, may be used to enable the problem to be approached quantitatively. Under the general headings: direct, refracted, reflected, and diffracted energy, air waves, surface waves, ghost reflections, simple multiples, complex multiples, diffractions, reflected refractions and refracted reflections are discussed. An example of a simple analytical attempt to solve an unusual offshore multiple problem is briefly described.

INTRODUCTION

With the advent of magnetic tape and the various types of display sections—variable area, variable density, full trace, partial trace—to mention a few, the seismologist finds himself in a position to devote more time to what might be termed the finer points of interpretation. More and more does he find it opportune and moreover desirable to look beyond the conventional reflections on his seismogram, to the so-called anomalous events, which though often obscure and difficult to identify, nevertheless can contribute much to

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the quality of his interpretation. This paper aims at briefly describing the various anomalous events encountered from time to time on the reflection seismogram, pointing out their significance and suggesting here and there a method of identification. No attempt has been made to treat so large a subject exhaustively.

ANOMALOUS EVENTS

It is convenient for our purpose to place the seismic energy resulting from a subsurface explosion into four principal categories, viz. direct, refracted, reflected, and diffracted energy. Events recorded on the conventional reflection seismogram may be not only the visual effect of each of these types of energy reaching the surface of the ground, but the combined effect of two or more.

In general the anomalous events to be found on the seismogram are due to energy being either reflected or diffracted. Refraction, which strictly speaking is an essential part of the normal reflection process in a heterogeneous medium, may also play a major role in producing an anomalous event. Such an event is the refracted reflection probably encountered where media of sharply contrasting elastic moduli occur side by side such as across some faults of fairly large movement.

We shall now examine the events associated with the various types of energy already listed.

Direct Energy

Direct Energy (e.g. air waves and surface waves) is generally easy to recognize.

Air waves may appear on the seismogram when a charge is detonated too near the surface, or as the result of casing or debris being blown out of the shot hole and making impact with the ground. The resulting event can be identified by its large move-out representing a velocity equal to that of sound in air.

Surface waves generally occur in the form of so-called (and undesirable) ground roll. These waves are probably primarily of the Rayleigh type, a combined longitudinal and transverse wave with its plane of oscillation at right angles to the surface and parallel to the direction of the propagation. In many cases the surface wave shows characteristic frequencies that are much lower than those of reflections and this aids in their identification. Since the ground roll often has a velocity more or less equal to the weathering velocity it also can be identified by its large move-out. The peculiar characteristics of the surface wave suggest means for its elimination, and procedures by which this is achieved are fairly standard. They include filtering, compositing, multiple geophones and offset of shotpoint.

The direct wave is not necessarily undesirable. For example in offshore seismic surveys where the velocity of sound in water is often of the same order as that in the underlying formation, and because it often becomes necessary to place charges close to the surface in order to eliminate the "bubble effect," direct energy provides the "first breaks," the energy travelling through the water medium. In this particular instance the direct wave plays an important and necessary part in determining the location of the shot with respect to the seismometers.

Refraction Energy

Refracted energy usually takes the form of first arrivals on the reflection seismogram and performs a definite function in interpretation. In instances where long spreads are employed for velocity measurements, or if shotpoint offset is considerable, refractions may be recorded from below the weathered layer and interfere with the reflected energy. This imposes one limiting factor on the practical length of reflection spreads.

Reflection Energy

Reflected energy forms the principal source of useful recorded data, and occasionally the principal source of anomalous events, the multiple reflection.

Multiple reflections are often placed in various categories: the *ghost reflection* (Figure 1), or a multiple composed of energy from the shot first travelling upwards, then being reflected, usually from the base of the weathering, down into the section where it is again reflected; the *simple multiple*, comprising a normal reflection at an interface followed by reflection at the surface or near surface, this in turn followed by reflection once more at the interface; *complex multiples* where more than two interfaces are involved (Figure 2).

Ghost reflections produce interference resulting from the out of phase relationship between the normal down travelling incident wave and the ghost. The effect is distortion of the wave form. A

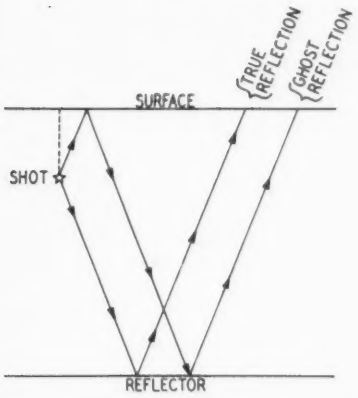


FIG. 1. Ghost reflection diagrammatically shown.

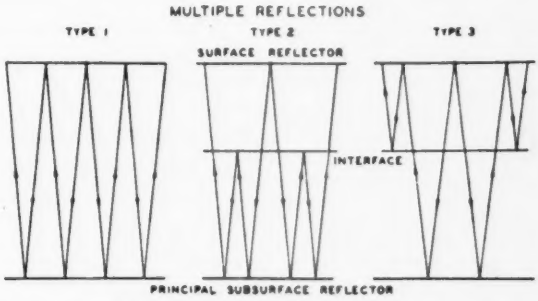


FIG. 2. Multiple reflections diagrammatically shown.

method of demonstrating the existence of ghost reflections is to produce a synthetic seismogram by recording, by means of a single seismometer, a number of shots at various depths. Ghost and normal reflections will be indicated as alignments dipping in opposite directions (Figure 3). To eliminate ghost reflections, seismograms from shots at different depth can be composited using magnetic tapes, with a time shift equal to the difference in shot depth divided by the appropriate velocity. Normal reflections will be added in phase, whereas ghosts will tend to cancel each other.

Van Melle and Weatherburn (1953) have described how Primacord may be used both to demonstrate and eliminate ghost reflections.

The Primacord was wound in the form of a vertical helix in such a way that the explosion kept pace with the seismic wave-front propagated in a vertical direction. It was found that when the

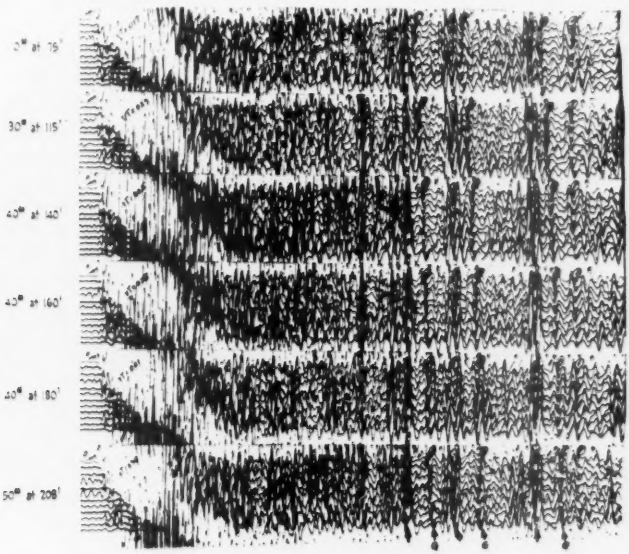


FIG. 3. Six seismic records made from same hole showing ghost reflections converging on true reflections. (Hammond and Hawkins)

detonator was placed at the top of the columnar charge no ghosts were recorded; when at the bottom, the ghosts predominate, due to the breaking up of the direct wave.

Some interesting observations on ghost reflections have been made by Hammond and Hawkins (1958). The authors conclude that "ghost reflections probably cause more variation in record character between successive shots and between successive holes than any other factor."

Simple multiples are probably the easiest to identify. In some instances an erratic dip on the seismic section will indicate the presence of the multiple. Simple multiples have more or less a direct dip and depth relationship with the primary, provided the primary has small dip. In other words, a first multiple will appear to be at approximately twice the depth of the primary reflection and have roughly twice the dip; second multiples will have roughly three times the depth and dip; and so on.

Where the length of spread is sufficiently great another characteristic of the multiple may be used to advantage. Reflections arriving from reasonably shallow interfaces show marked curvature on the seismogram. The amount of curvature is referred to as normal move-out. For a flat reflector, normal move-out is defined as the difference in arrival time between seismometers at the shotpoint and end of the spread respectively. It is evident that the normal move-out increases with increased spread length.

For symmetrical split spreads and where dip is not excessive, normal move-out for either half of the spread can be closely approximated by taking half the algebraic sum of the move-out on either side of the shotpoint. That is, if t_1, t_{12}, t_{13}, t_{24} represent reflection times referred to seismometers 1, 12, 13 and 24 respectively of a standard 24 seismometer split spread, then normal move-out $\Delta t_N/2$, is approximately equal to

$$\frac{(t_1 - t_{12}) + (t_{24} - t_{13})}{2}.$$

The quantity Δt_N, total normal move-out, has some useful properties (Seabrooke and Woo, 1954). A very good approximation relating average velocity of travel $\overline{V}$, spread length $2x$, normal reflection time t_0 (roughly the average of the two inside reflection times t_{12}, t_{13}) and normal move-out for reflectors of zero dip is:

$$\Delta t_N = x^2/\overline{V}^2 t_0.$$

Now a typical velocity-depth function for many areas is given by the equation:

$$\overline{V} = V_0 + 2kZ,$$

where $\overline{V}$ is again average velocity to a reflector at depth Z, V_0 is the initial velocity at the assumed datum plane i.e. where $Z=0$, and k is a constant (acceleration factor).

We can combine these two equations to obtain the relation:

$$\sqrt{t_0 \Delta t_N} = x(1 - kt_0)/V_0.$$

This represents a straight line of slope $S = -kx/V_0$, intercept $I = x/V_0$ with t_0 abscissa, $\sqrt{t_0 \Delta t_N}$ ordinate.

A graph of t_0 against $\sqrt{t_0 \Delta t_N}$ can be informative.

Consider the case of a simple type multiple where energy reverberates between two parallel horizontal layers. If $\overline{V}$ = average velocity of the intervening medium, then it can be readily shown that the product of normal move-out and arrival time, $t_0 \Delta t_N$, is a constant. Thus, the graph of $\sqrt{t_0 \Delta t_N}$ against t_0 shows a straightline of zero slope where $\overline{V} = x/I$ (Figure 4).

For a seismogram of bona fide reflections only, the same graph gives a sloping line, its gradient and intercept being dependent on the particular velocity distribution (Figure 5).

The conditions under which a line of zero slope will be obtained rarely occur on land, though in offshore work one encounters numerous excellent examples. Usually simple multiples when present are intermixed with bona fide events. The $\sqrt{t_0 \Delta t_N}$, t_0 graph then shows an erratic distribution of points and a best straight line fit will give a slope varying from zero to that for no multiples. The effect of dip of the primary reflector is of course important (Figure 6); where this is small, say 5 degrees or less, it can be neglected, but for larger values the added complication exists that the graphs for both bona fide and multiple reflections are essentially alike. It then behooves the interpreter to use other criteria. The technique of inspecting the seismogram for repetition of waveform has been successfully used by some.

Under the heading *Complex multiples* we shall attempt to show how a combination of techniques

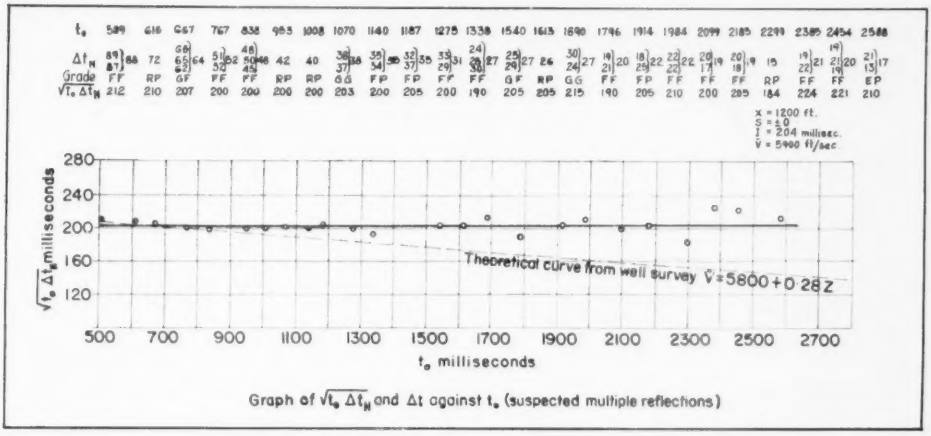

x = 1200 ft.
S = ±0
I = 204 millisec.
V = 5900 ft/sec
Theoretical curve from well survey V = 5800 + 0.28Z
t₀ milliseconds
Graph of √t₀ Δt_N and Δt against t₀ (suspected multiple reflections)

FIG. 4. Graphical representation of seismogram containing largely multiple reflections.

may be used in an effort to analyze a particularly troublesome multiple offshore area.

Complex multiples are extremely difficult to identify. The apparent dip indicated by the complex or inter-bed multiple is dependent upon the dip of both reflecting interfaces. The ability to distinguish complex multiples from simple multiples or from bona fide events on the basis of erratic dip alone will in turn be dependent upon the normal dip-depth relationship encountered in the section, and also the particular interfaces involved. However normal move-out can be used to some advantage. Perhaps a brief account of an actual example will illustrate one way in which the problem can be approached. Once more the seismograms examined were obtained from an offshore survey. In offshore work many of these phenomena occur in greater abundance than on land, thereby providing the seismologist with much useful data from which to increase his understanding of the subject.

The existence of a severe simple multiple problem in the area had been determined beyond reasonable doubt by some excellent examples of interbed reverberation as indicated on the $\sqrt{t_0 \Delta t_N}$, t_0 graphs, supported by obvious dip-depth rela-

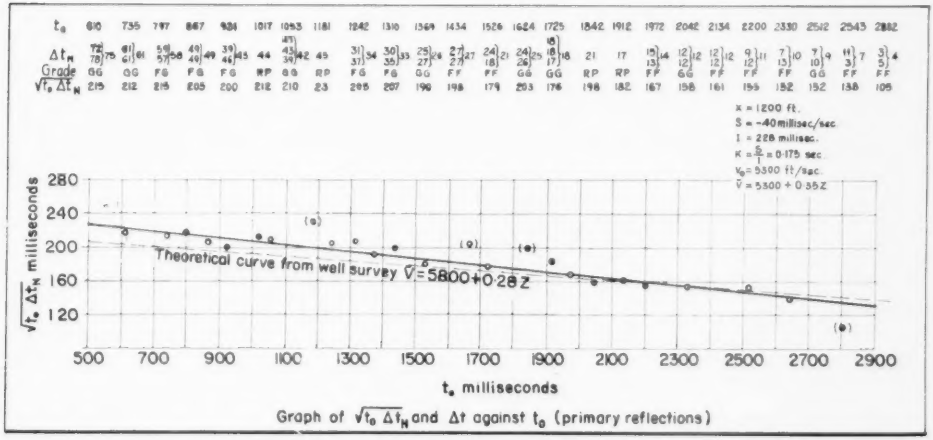

x = 1200 ft.
S = −40 millisec/sec
I = 228 millisec.
K = S/I = 0·175 sec
V₀ = 5300 ft/sec.
V = 5300 + 0·35Z
Theoretical curve from well survey V = 5800 + 0·28Z
t₀ milliseconds
Graph of √t₀ Δt_N and Δt against t₀ (primary reflections)

FIG. 5. Graphical representation of seismogram containing largely primary reflections.

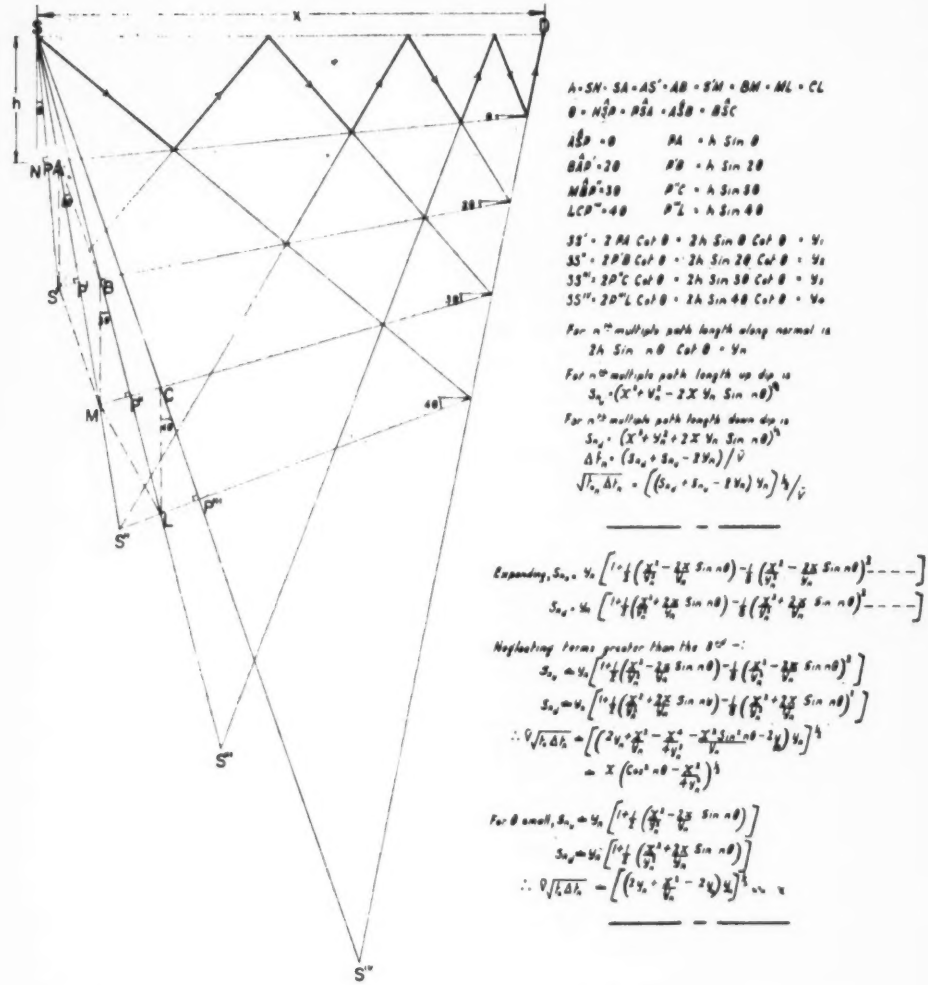


FIG. 6. Use of image points to derive Δt_N, t_0 relationship for multiple reflections from dipping reflector.

tionships. However, many of the seismograms, though bearing strong resemblance in character and general appearance to those containing little but simple multiples, exhibited unusual Δt_N, t_0 relationships.

A line of interlocking profiles was taken, and graphs showing average velocity $\overline{V}$ (calculated from Δt_N) against t_0 for all reflections were made for each seismogram. Since the velocity distribution in the general area was known from well data, it was possible to compare these graphs with a theoretical curve. In all, 17 seismograms were analyzed. The graphs were interesting. In general, scattering of the points was not excessive so that it was a relatively simple matter to determine trends. At one end of the line the points indicated a *decrease* in average velocity with arrival time (Figures 7–11). Proceeding shotpoint by shotpoint successive graphs showed a gradually increasing acceleration factor, the seismograms at the other end of the line exhibiting a more or less normal looking increase in velocity with arrival time (Figures 12–16). From a point of view of appearance, nearly all seismograms were quite

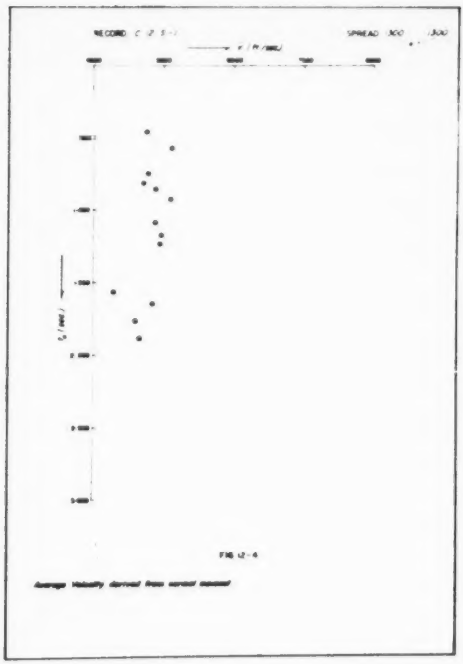


FIG. 7

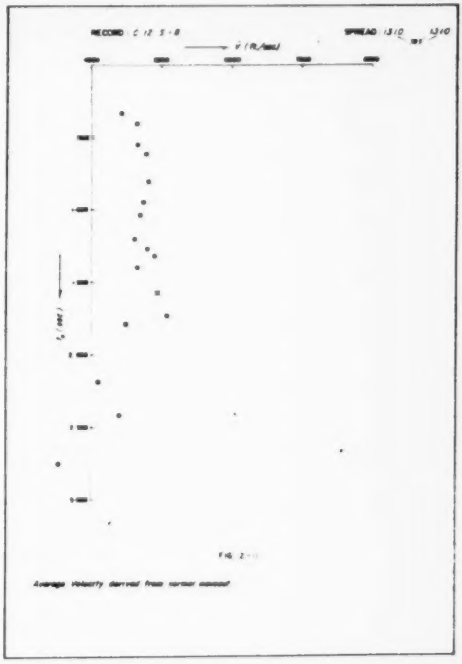


FIG. 9

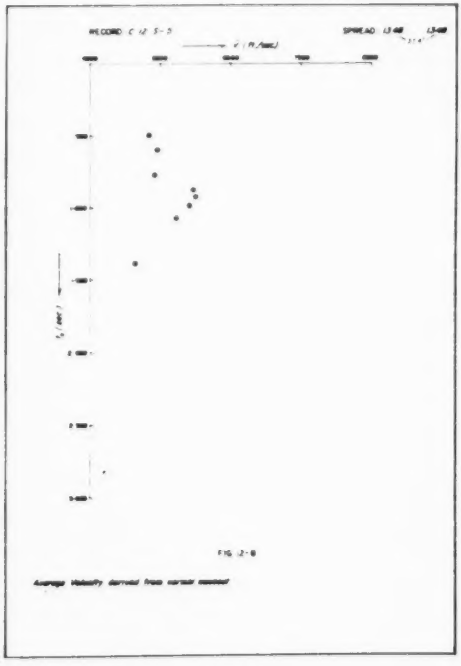


FIG. 8

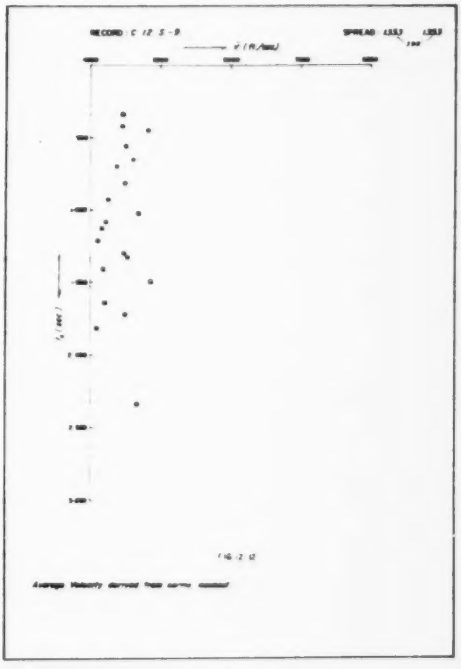


FIG. 10

(*Legend for Figures 7–11 follows on page 92*)

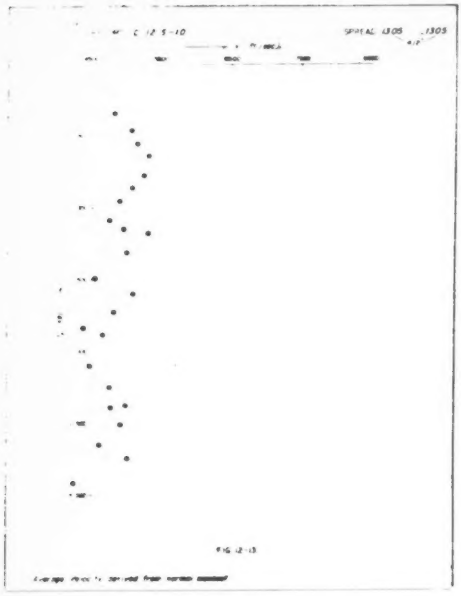


FIG. 11

FIG. 7-11—Graphs from seismograms showing decrease in average velocity with time (one end of line).

similar. It was difficult to believe that certain seismograms could contain largely multiple reflections and adjacent ones largely bona fide events. A migrated dip section prepared on the assumption that all events were bona fide reflections gave some indication that multiples were present as evidenced by the crossing of dip segments at depth where a slight turnover occurred near the surface. Dip along the line was rather gentle and the apparent increase with depth, though somewhat uniform, was not necessarily suspicious.

The nature of the $\overline{V}$, t_0 graphs gave the probable explanation, later to be supported by inspection of the seismograms. Here is a typical line of reasoning applied to one particular $\overline{V}$, t_0 graph that showed a decrease in average velocity with arrival time (Figure 9):

(1) Multiples are present from a small number of relatively shallow primaries as evidenced by the low average velocities.
(2) Both simple and complex multiples might be present as suggested by the slight slope of the $\overline{V}-t_0$ curve.
(3) The general decrease in average velocity with reflection time would indicate the path of complex multiples to consist of an initial reflection from a relatively shallow bed followed by repeated reverberations between a shallower re-

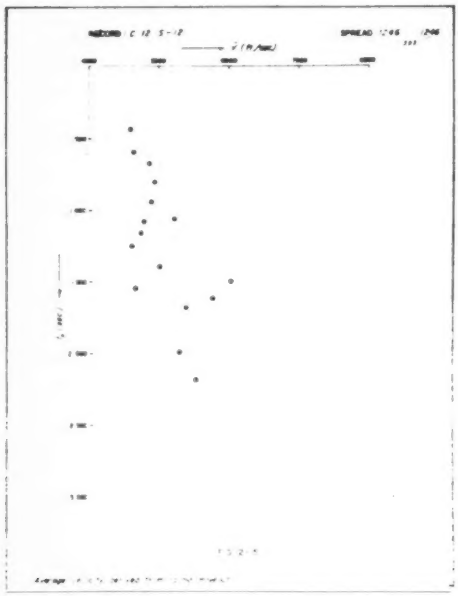


FIG. 12

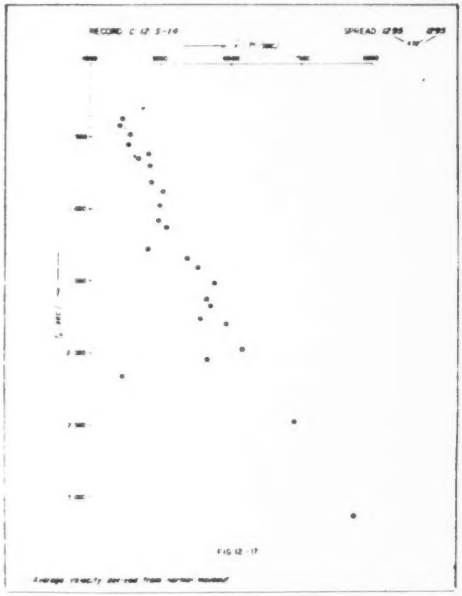


FIG. 13

(*Legend for Figures 12–16 follows on page 93*)

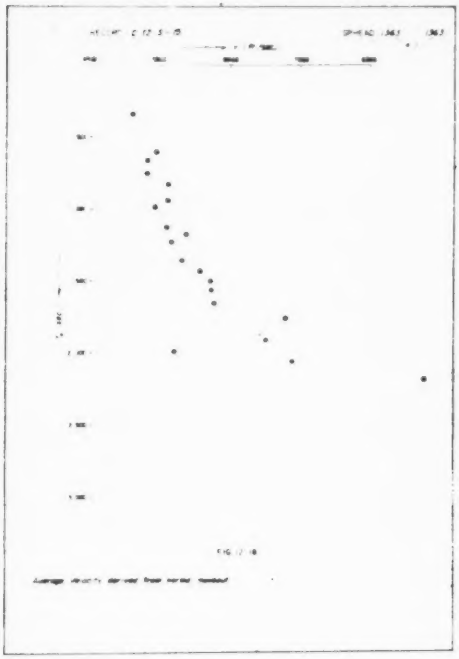


FIG. 14

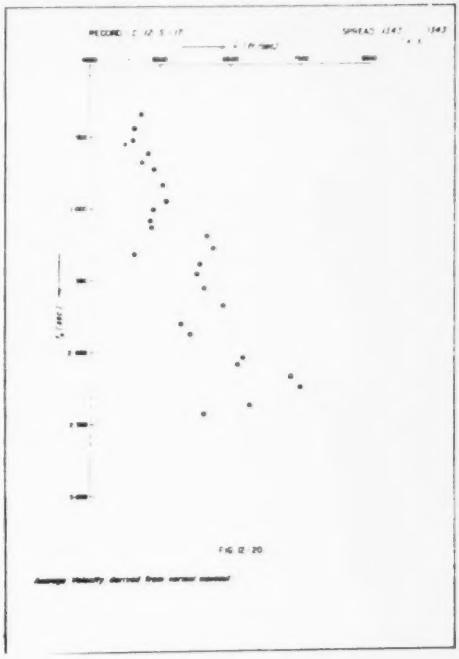


FIG. 16

FIG. 12–16. Graphs from seismograms showing increase in average velocity with time (other end of same line).

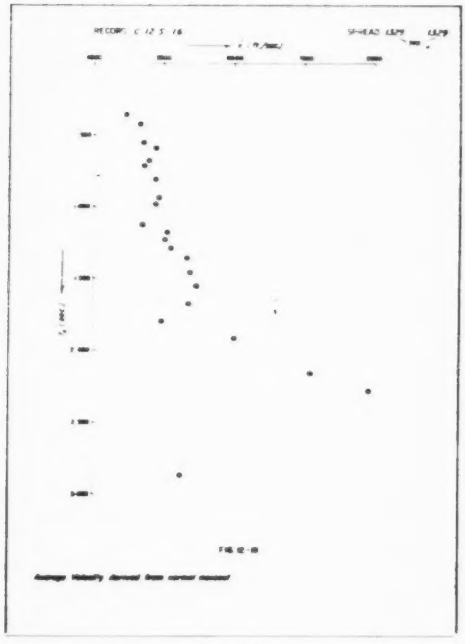


FIG. 15

flector and probably the surface. Thus the value of $\overline{V}$ from each successive multiple gradually decreases, starting with the average velocity to the primary (deeper) reflector and approaching the average velocity to the secondary (shallower) reflector.

Upon examination of the seismogram (Figure 17) it was found that, from the point of view of arrival time and character, though events persisted to at least 3.0 sec., there was probably little of value beyond 0.6 sec. Five closely spaced apparently bona fide reflections were present at the front end of the seismogram, say A, B, C, D, E. Reflection B was of considerable amplitude and provided a series of simple multiples between reflector B and the air-water interface. The time intervals between these multiples constituted a number of "windows." Through the first of these windows appeared the primary events C, D, E. Through subsequent windows were to be found complex multiples formed by the initial reflected energy from reflectors A, C, D and E reverberating between the surface and reflector B.

Velocities and densities were assigned to the

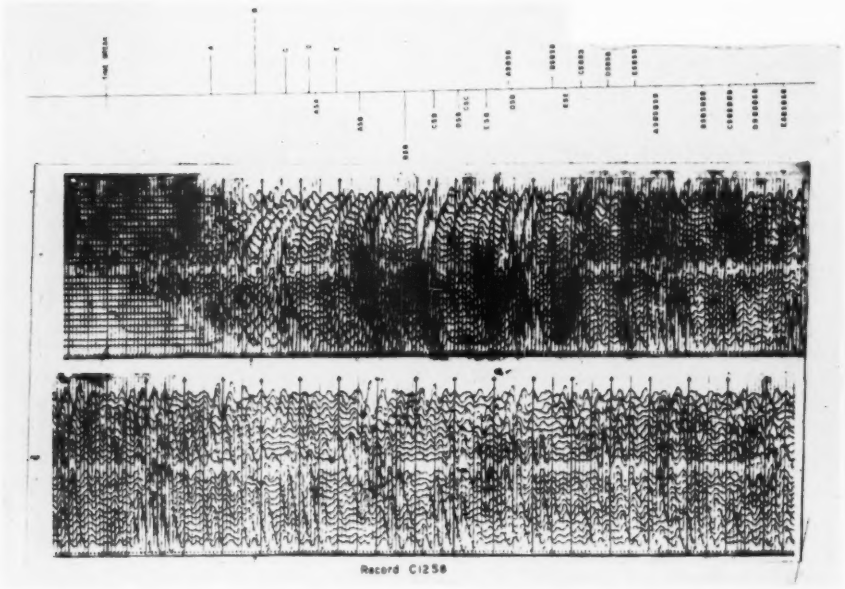


FIG. 17. Seismogram and theoretical synthetic showing multiple reflections, average velocity decreasing with time (refer Figure 9).

layers A, B, C, D, E, and corresponding reflection coefficients derived and used to make a synthetic seismogram. The latter is shown diagrammatically above the seismogram in Figure 17.

Other seismograms were analyzed in similar fashion. The process was essentially the same in all cases. Lateral changes of reflection coefficient resulted in a shift of emphasis. Where average velocity appeared to increase with arrival time, the interbed multiples were confined to an interval of relatively high velocity. Figure 18 shows the seismogram from which the data in Figure 12 have been derived. On this seismogram dip stepouts were somewhat larger than seen in Figure 17 described above. They were also rather erratic, that is to say there was no obvious dip-depth relationship in evidence. This was also one of those seismograms which exhibited a general increase in average velocity with reflection time. The following is extracted from a report on the study of the problem and illustrates the manner in which the various evidence was utilized:

"In attempting to interpret seismogram 12, the obvious approach is to first consider the most simple model, then introduce additional layers as required. The relatively low average velocities indicated by the delta-t analysis suggest a fairly shallow interval for the interbed multiples. Assuming reflector B to be one necessary element we must search for a deeper layer of adequate dip to satisfy the dip stepout conditions. Reflector E appears suitable. In selecting reflector E as a second element we are implying that between shotpoints 8 and 12, transition has taken place in terms of reflection coefficient. A sand development appears to be the most likely explanation. The model at this stage differs only slightly from that selected for seismogram 8, the important change being the increased reflection coefficient attributed to reflector E. A study of the predicted events from this simple model indicates that we need introduce no additional layers to interpret the salient features of the seismogram. Even the seemingly erratic dips can be rationalized in terms of interbed multiples. We conclude therefore that *the events on this seismogram consist largely of simple and complex multiples from relatively shallow source, and that the useful data are probably confined to the first 2000 ft.*"

Close comparison of the entire series of seismograms revealed subtle changes in reflection quality from shotpoint to shotpoint, some reflections gradually growing weaker, while others increased in strength.

Before proceeding to the next topic, diffractions, it should be pointed out that outstanding reflectors of high reflection coefficient are not essential for the multiple process to be possible. It can be demonstrated that a series of thin beds each of which has relatively small acoustic impedance can combine to simulate a strong reflec-

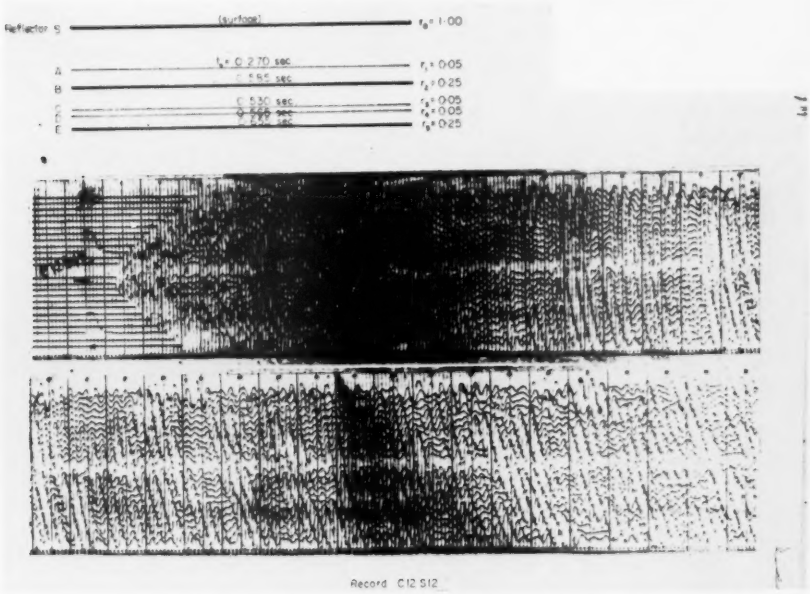


FIG. 18. Seismogram (with model) showing multiple reflections, average velocity increasing with time (refer Figure 12).

tor capable of sustaining numerous multiples. Thus, in the examples given above, whereas the low reflection coefficients assumed in Figures 17 and 18 were reasonable for the area, no known beds existed to provide the higher values necessary. However, sand-shale sequences capable of simulating a single strong reflector were not uncommon and these are presumed to provide reflectors B in Figure 17, B and E in Figure 18.

Diffraction Energy

Diffractions have been defined thus: "The term diffraction is used to designate a phenomenon that occurs when travelling waves strike the edge of an obstacle in their travel path. It can be shown theoretically that the edge reradiates the incident energy as if the edge were a source of sound." Faults, pinchouts, reef edges, sudden facies changes, abrupt changes in dip, etc. may act as obstacles and produce diffractions.

Though it is difficult to distinguish between bonafide reflections and diffractions on a seismic record, certain criteria can be applied. Dix (1952) points out as one of the distinguishing characteristics of a diffraction the excessive normal move-out as compared with a true reflection, since the origin of the diffraction is much shallower than the image point of the reflection. Possible diffractions may be identified by comparing the normal move-out of the event with that of a true reflection at half the arrival time.

Hagedoorn (1954) has introduced the concept "curve of maximum convexity" which is the apparent horizon formed by the diffracted energy (Figure 19). Such curves may be deduced from a wave front chart and can be of assistance in identifying diffractions (Figure 20). Record sections, which enable the seismologist to view simultaneously a large number of traces, should prove indispensable in locating curves of maximum convexity.

Energy considerations are perhaps the crux of the matter. It seems to be generally accepted, perhaps erroneously, that a diffraction will appear as a weak appendage to a bonafide reflection. Krey (1952) has worked out mathematically the rate of decay of the diffraction energy as a function of distance. Discussing the occurrence of diffraction energy at faults he writes: "It can be shown, for instance, that the fault begins where the reflection amplitude is equal to half of the normal amplitude. But with the superposition of distorted waves and with modern techniques of full automatic gain control, it should be extremely

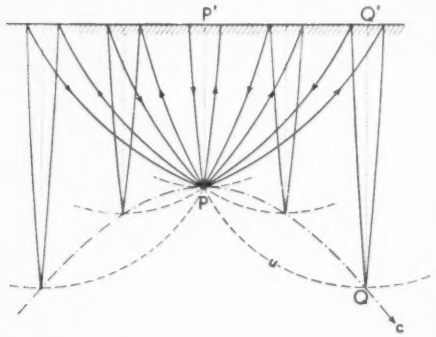


FIG. 19. Curve of maximum convexity or vertically plotted horizon from single reflecting point. (Hagedoorn)

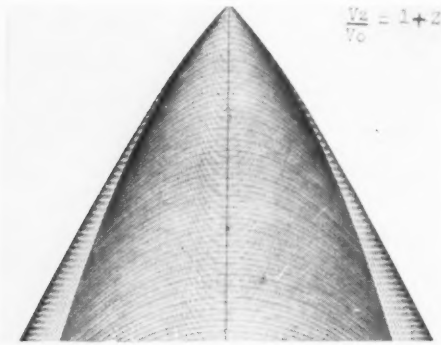


FIG. 20. Chart showing curves of maximum convexity, derived from wave-front chart. (Hagedoorn)

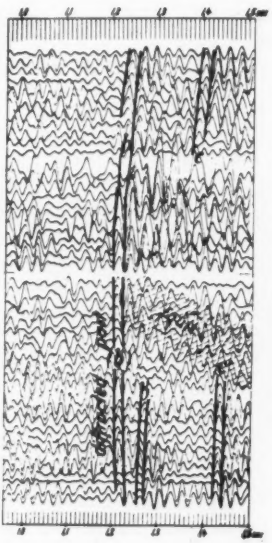


FIG. 21. Diffraction at a fault. (Krey)

will appear strong only when it is strong relative to the noise background. This means that the observed fluctuating variation in energy refers to an inverse fluctuation of the recorded noise and not, necessarily, to a variation of the energy of the event." Others have similarly identified diffractions which exhibit amplitudes comparable with other events interpreted as reflections. It is probable therefore that diffractions, especially in the difficult to recognize the true magnitude of reflected impulses." In fact Krey, in his paper, gives examples of diffractions at faults showing quite appreciable amplitude on the seismogram (Figure 21). Hagedoorn shows a half-curve of maximum convexity extending approximately 1.5 kilometers displaying appreciable signal strength (Figure 22). He comments: "The apparent variation of the energy along the curved event is certainly no measure of its real energy content. The automatic volume control of the recording instrument reduces the amplitude to a certain level within a certain time lag. The event

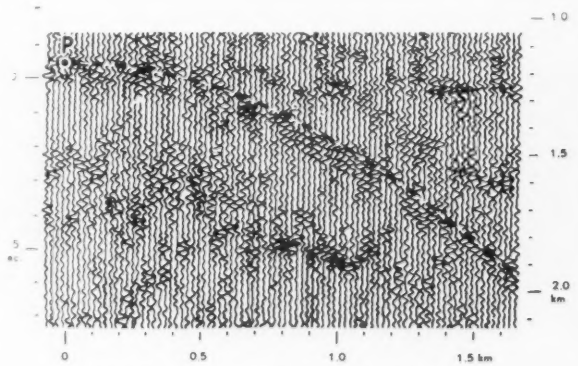


FIG. 22. Seismic record section showing diffraction curve. (Hagedoorn)

FIG. 23. Reflected refractions or near surface diffractions. (Ellis and Winterhalter)

immediate area of the discontinuity, may appear indistinguishable from reflections insofar as signal strength is concerned.

Where diffractions are treated as reflections and accordingly migrated they often appear on a section as anomalous dips in the approximate position of the discontinuity. Since it is usually desirable to locate such discontinuities (faults, reefs, etc.) as accurately as possible, recognition of a curve of maximum convexity and hence its apex becomes of considerable advantage. As has already been stated, record sections, where available, with the aid of theoretical maximum convexity curves drawn to scale, should greatly assist in identifying diffracted energy. In the normal course of interpretation where data are transferred from seismic records to migrated sections, one practical approach to the problem might be made by following this procedure:

(1) Plot events suspected of being diffractions (excessive normal move-out, steep apparent dips etc.) vertically on the section, using end and center times and joining with straight lines. Use a suitable distinguishing mark to identify these events.
(2) Attempt to fit one or several such events to a curve of maximum convexity derived from a wave-front chart.
(3) Note the apex of the curve chosen. This locates the discontinuity.

Reflected refractions are essentially diffractions. The term is generally applied to those abnormal events characterized by large stepout, low frequency and considerable energy content. These abnormal diffractions are probably produced by irregularities just below the surface; on land pre-

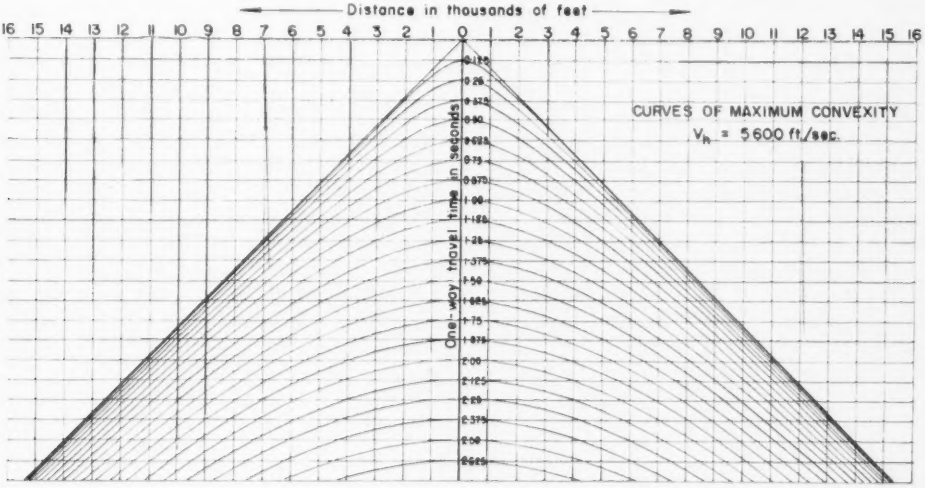

Distance in thousands of feet
16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
One-way travel time in seconds
CURVES OF MAXIMUM CONVEXITY
V_h = 5600 ft./sec.

FIG. 24. Chart of curves of maximum convexity for reflected refractions.

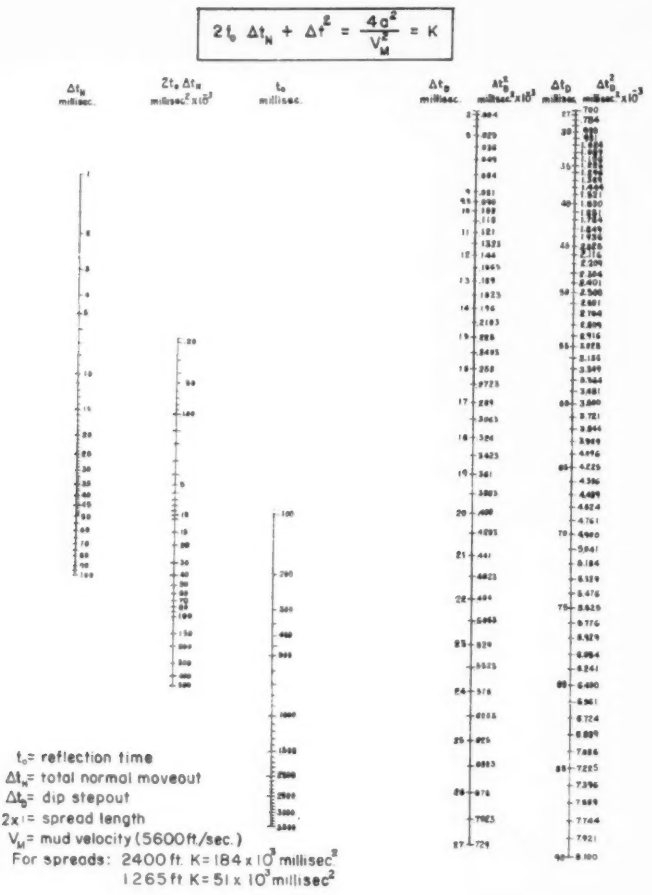

$2t_o\,\Delta t_N + \Delta t^2 = \frac{4a^2}{V_M^2} = K$
Δt_N millisec.
$2t_o\,\Delta t_N$ millisec^2 x10^3
t_o millisec.
Δt_D millisec.
Δt_D^2 millisec^2 x10^3
Δt_D millisec.
Δt_D^2 millisec^2 x10^3
t_o= reflection time
Δt_N= total normal moveout
Δt_D= dip stepout
2x = spread length
V_M= mud velocity (5600ft./sec.)
For spreads: 2400 ft. K= 184 x 10^3 millisec^2
1265 ft. K= 51 x 10^3 millisec^2

FIG. 25. Nomogram for identifying reflected refractions.

sumably at the base of the weathered layer, at sea in the ocean floor. Energy travels out from the shotpoint horizontally, strikes the obstacle and is diffracted, each point on the diffractor acting as a new source. Frequently considerable energy is contained in these events. Occasionally offshore seismograms have been encountered that contain exclusively reflected refractions.

Reflected refractions from a single diffraction point should align themselves along a curve of maximum convexity. Ellis & Winterhalter (1956) show an excellent example of such a curve extending across no less than 11 interlocking profiles (Figure 23). The curves of maximum convexity for reflected refractions differ from those previously referred to for normal diffractions in that the velocity of travel is constant (Figure 24). This velocity may be determined by treating vectorally correlated events obtained from two spreads at an angle to each other and with a common shotpoint. Provided the diffracting point subtends a fairly acute angle with the seismometer spread, the reflected refractions will have essentially linear time-distance relationships. Ideally where the diffractor is in the line of spread a direct value of velocity can be obtained from a single component.

Using appropriate curves of maximum con-

vexity the location of the obstacle can be accurately determined by fitting any two correlated events. Even where single components only are available it is possible, by treating a large number of events from a grid of intersecting lines, to obtain the most logical source for the reflected refractions.

Another suggested application for these curves is in the identification of reflected refractions. Where a seismometer spread is located broadside to the diffractor, it may be difficult for the seismologist to distinguish between bonafide reflections and reflected refractions, since the latter will no longer be characterized by large stepout. By noting the location of the apex of the curve of maximum convexity fitted to a more obvious abnormal event, it becomes possible to select the appropriate seismogram and identify a reflected refraction previously picked as a reflection.

Since a reflected refraction from a point source can be made to fit a curve of maximum convexity, the three quantities, arrival time t_0, apparent dip stepout Δt_D and total normal move-out Δt_N, all readily obtainable from the seismogram, will serve to identify an event.

Without going into details it can be shown that where $2a$ = spread length (split spread), V_h = horizontal velocity of travel, then (approximately):

$$4x^2/V_h^2 = 2\Delta t_N t_0 + \Delta t_D^2$$
$$= \text{constant for a given area.}$$

From this equation a simple nomogram (Figure 25) can be constructed from which the likelihood of an event being a reflected refraction can be quickly established.

REFRACTED REFLECTIONS

Refracted reflections are simply reflections that undergo appreciable refraction before returning to the surface. Unconformities and faults may provide sharp velocity contrast across adjacent interfaces. This velocity contrast results in bending of the emergent ray and introduces an erroneous dip. It is quite conceivable that reverse dips might be recorded in the vicinity of a fault and lead to an incorrect interpretation (Figure 26). In such circumstances it is advantageous to have other data, such as gravity or refraction, from which to establish the location of the fault.

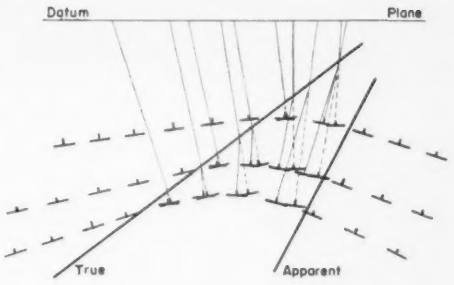


FIG. 26. Refracted reflections may lead to incorrect interpretation. Fault appears displaced to the right of true position.

ACKNOWLEDGMENT

The Author wishes to express his appreciation to California Exploration Company for permission to publish this paper.

EDITOR'S NOTE:

Reproduction of the illustrations for this article is noticeably below GEOPHYSICS standards. Circumstances beyond the author's control prevented redrafting the originals. The Editor chose to print the figures as they are, rather than delay publication of the paper.

REFERENCES

Dix, C. H., 1952, Seismic prospecting for oil: Harper and Brothers, p. 236.
Ellis, L. G., and Winterhalter, A. C., 1956, Unusual events in offshore seismics: Geophysics, v. 21, n. 2.
Hagedoorn, J. G., 1954, A process of seismic reflection interpretation: Geophysical Prospecting, June.
Hammond, J. W., and Hawkins, J. E., 1958, Getting the most out of present seismic instruments: Geophysics, v. 23, no. 3.
Krey, T., 1952, Significance of diffractions in investigation of faults: Geophysics, v. 17, no. 3.
Van Melle, F. A., and Weatherburn, K. R., 1953, Ghost reflections caused by energy initially reflected above the level of the shot: Geophysics, v. 18, no. 3.

DISCUSSIONS AND COMMUNICATIONS

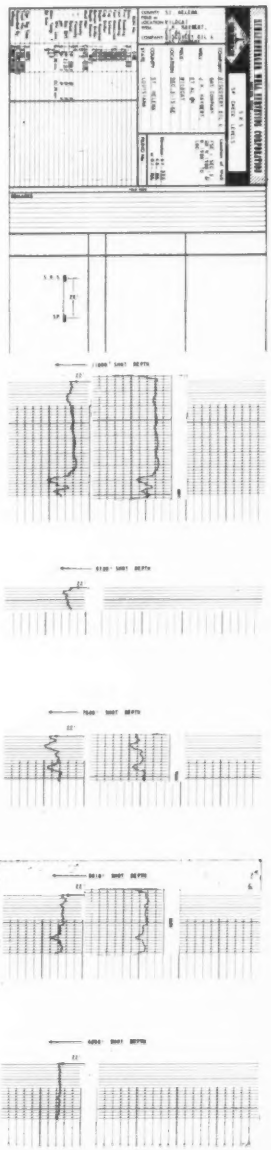
ACCURATE DEPTH DETERMINATION OF THE VELOCITY SURVEY WELL PHONE*

R. P. NOLTING†

Many velocity surveys have been shot in which the actual depth of the well phone was in question at one or more of the levels shot in the borehole. The computed time to the questioned level would not fit the other data obtained from the velocity survey, i.e., the data from the questioned level would not fit the time-depth curve within reason or, more recently, it could not properly be fitted to the corrected continuous velocity log data. If the "first break" of the questioned level could not be repicked to conform to the other data, a notation was made in the velocity survey report that the depth of the well phone was *probably* in error. Although this assumption was correct in many cases, there are various other reasons why data from one check level should not fit the rest of the data.

Accurate depth control of the well phone can be established by fully utilizing the geophysical tools that are normally run in the borehole. Most velocity surveys that are now being run are shot with the well phone and the other logging equipment connected together into one logging tool. Depth control of the well phone can be determined by running a section (100 ft) of one of the standard logs either immediately before or after the check level is shot. This section of log can be correlated to the standard log and the depth of the well phone established from this correlation. An example of a S.R.S. check level log correlated at several depths to the S.P. log taken from the standard log is shown in Figure 1.

Mobil Oil Company has used this technique for most of the wells they have surveyed recently. Although no large depth discrepancies have been noted (20 ft the largest), the computed time values do not always fit the other data reasonably. Since depth control is established for the "misfit" points, we can now attempt to explain these "misfits" and possibly learn more about the problems of obtaining reliable check shot data.



* Received by the Editor October 22, 1960.

† Mobil Oil Co., Dallas, Texas.

DISCUSSION OF "*LOG INTERPRETATION IN SANDSTONE RESERVOIRS*," BY M. R. J. WYLLIE, GEOPHYSICS, AUGUST 1960, pp. 748–778.

L. DE WITTE*

In his article on log interpretation in sandstone reservoirs, under the heading: "The Determination of Resistivity Index," Dr. Wyllie reviews the history and present status of the so called "shaly sand problem."

By comparison with recent laboratory experiments the author shows that for the case of disseminated clay content in sandstones, the most reliable determination of percentage water saturation is that made according to a method proposed by A. J. de Witte in 1957. Dr. Wyllie points out that A. J. de Witte's method has not been widely used because its derivation was intuitive (rather than theoretical). Surprisingly enough the author seems to be unaware of the fact that the relations proposed by A. J. de Witte and confirmed by Wyllie's recent data are not at all new, but were published two years earlier as derived by a coherent and concise theoretical treatment of the electrochemical behavior of shaly sands. The publication in question is given below.[1] It was first presented at the 1954 A.I.M.E. fall meeting in San Antonio and subsequently published in the Journal of Petroleum Technology of July 1955.

Specifically, Dr. Wyllie's equation (6) which is equation (9) in the paper by A. J. de Witte,[2] and reads:

$$\frac{1}{R_t} = AS_w + \frac{BS_w^2}{R_w} \quad \text{(footnote 2 (9))}$$

was given in reference 1, equation (26) as:

$$\frac{1}{R_t} = \frac{C}{F}(m_R/S_w + 2.15m_w)S_w^2 \quad \text{(footnote 1 (26))}$$

where F is the formation factor

m_R = the equivalent concentration of fixed charges due to clays in the interstital solution.

m_w = molality of connate water (approximately proportaional to $1/R_w$).

$C = 96.5\ \beta\ u_A$ with

β = conversion factor of normality to molality for the salt solution in question.

u_A = mobility of anions.

It is readily seen that the two equations are identical except for the fact that A. J. de Witte's unspecified coefficients A and B are in the earlier work described in detail in terms of the physical and electrochemical characteristics of the system.

In the same fashion all the other relations for resistivities and potentials in shaly sands proposed by A. J. de Witte are identical except for leaving the coefficients unspecified to those dervied by electrochemical theory in material referred to in footnote 1.

As an aid to future reviewers of the shaly sand problem, I should like to offer the following correlation chart for the relations derived at by "intuition" in material referred to in footnote 2 and those derived two years earlier by physicochemical theory in material referred to in footnote 1:

TABLE 1

Subject	Equation Number Ref. 2 (1957)	Equation Number Ref. 1 (1955)
Resistivity of water sands	2	20, 21
Resistivity of oil sands	9	25, 26
SP of shaly water sand	155 17	225 18
SP of oil sands	18, 18a	23
R_{xo}/R_t	19	Equation preceding (27)

It should further be mentioned that A. J. de Witte already presented experimental evidence in support of equation 2 (9) or 1 (26) in figure 3 of reference 2, although he does not indicate the source of the experimental data.

It is also noteworthy that field test results showing the applicability of the shaly sand relations of reference 1 to the determination of resistivity index and connate water saturation were reported as early as August 1955 by Blum and Martin.[4]

A. J. de Witte demonstrated (ref. 2 p. 91), on the basis of the assymptotic behavior for $S_w \to$ and $S_w \to 0$, that the constant k in his relation (8) which corresponds to C in Wyllie's relation[5] must be negligibly small or zero, thus these relations yield Wyllie's equation (6) and equation (9) of reference 2.

* Hughes Aircraft Co., Fullerton, California.

[1] Leendert de Witte, "A Study of Electric Log Interpretation Methods in Shaly Formations," *Journal of Petroleum Technology*, Vol. VII (7), pp. 103–110 (July 1955).

[2] A. J. de Witte, "Saturation and Porosity from Electric Logs in Shaly Sands," *The Oil and Gas Journal*, March 4 and April 15.

[3] A. Poupon, M. E. Loy and M. P. Tixier, "A Contribution to Electric Log Interpretation in Shaly Sands," *Transaction A.I.M.E.* 201, pp. 138–145.

[4] Harold A. Blum and John L. Martin, "Log Interpretation Problem in Low Resistivity Sands," *Journal of Petroleum Technology*, Vol. VII, no. 8, pp. 10–14 (August 1955).

[5] This equation is the important Tixier relation, proposed intuitively and empirically supported by M. P. Tixier et al. in 1954.[3] A theoretical derivation of the relation was given in reference 1 (1955).

REPLY TO DISCUSSION BY L. DEWITTE ON "*LOG INTERPRETATION IN SANDSTONE RESERVOIRS*"

M. R. J. WYLLIE

My sketchy discussion of the rather involved history of the "shaly sand problem" may indeed appear to underestimate Leendert deWitte's contributions and to favor unduly those of his brother Adriaan. I must crave Leendert's indulgence for I did not intend to leave an impression of fraternal discrimination. I drew particular attention to Adriaan's work because it was presented in the form of nomographs well suited to practical use and was, therefore, an easily available alternative to the familiar Schlumberger shaly-sand nomographs. Adriaan in his paper is careful to point out that his basic equations, although differently derived, are identical to Equations 23 and 26 in Leendert's earlier paper. Leendert may be pardoned for feeling that it was discriminatory of me not to have mentioned this since I noted, in a similar context, how much of Poupon, Loy and Tixier's scheme of interpretation was closely related to an earlier theoretical treatment by Doll.

If, however, Leendert is claiming that his interesting "coherent and concise theoretical treatment of electrochemical behavior of shaly sands" is also a complete treatment I must mildly disagree. His Equation 26 is certainly identical to Adriaan's Equation 9; however, both Adriaan in his Equation 8 and I in my Equations 3 and 5 explicitly note that the relationship between true resistivity and saturation is probably of the form $1/R_t = AS_w + BS_w^2/R_w + C$ and not simply of the form $1/R_t = AS_w + BS_w^2/R_w$.

DISCUSSION OF REVIEW OF "*INTRODUCTION TO GEOPHYSICS*," B. F. HOWELL, JR.

SHRI KRISHAN

In your February 1960 issue, there appeared a review of the book "Introduction to Geophysics" by Dr. B. F. Howell, Jr.

I want to point a flaw in the mathematical reasoning of the author. A publication of this and a subsequent explanation by the author will remove a great confusion in the minds of many readers.

Divergence of a vector $\vec{F}$ having components Fx, Fy, Fz in the x, y and z direction respectively is defined as:

$$\nabla \cdot F = \left(\frac{\partial}{\partial x}\hat{i} + \frac{\partial}{\partial y}\hat{j} + \frac{\partial}{\partial z}\hat{k}\right) \cdot (F_x\hat{i} + F_y\hat{j} + F_z\hat{k})$$

$$= \frac{\partial Fx}{\partial x} + \frac{\partial Fy}{\partial y} + \frac{\partial Fz}{\partial z} .$$

If F has components only in the x-direction then $F_y = F_z = 0$, i.e.,

$$\vec{F} = Fx\hat{i} + 0\hat{j} + 0\hat{k}$$

and

$$\nabla \cdot \vec{F} = \frac{\partial Fx}{\partial x} .$$

In Chapter X, page 148, vector $\vec{X}n$ is defined having components X_x, X_y, X_z only in the x-direction, i.e.,

$$\vec{X}_n = (X_x + X_y + X_z)\hat{i} + 0\hat{j} + 0\hat{k}$$

$$\therefore \quad \nabla \cdot \vec{X}_n = \{(X_x + X_y + X_z)\hat{i} + 0\hat{j} + 0\hat{k}\}$$

$$\cdot \left\{\frac{\partial}{\partial x}\hat{i} + \frac{\partial}{\partial y}\hat{j} + \frac{\partial}{\partial z}\hat{k}\right\}$$

$$= \frac{\partial X_x}{\partial x} + \frac{\partial X_y}{\partial y} + \frac{\partial X_z}{\partial z} .$$

The result derived by the author in equation (10.4) can not be represented by $\nabla \cdot \vec{X}n$ as he has pointed out in equation (10.7) and illustrated further by equation (10.7) on page 149.

CORRECTION

NOMOGRAMS TO SPEED UP SEISMIC REFRACTION COMPUTATIONS, GEOPHYSICS, OCTOBER, 1960.

TSVI MEIDAV

The last sentence in the paper "Nomograms . . . ," p. 1045 should read:

"Pass a line through i and Z and read off X, the offset distance." Also, a regrettable typist omission is present in the paper "An Electrical Resistivity Survey for Ground Water," and was not captured in reading the typed manuscript. The sentence before last on p. 1093 should read:

"The project was later concluded under the auspices of the Missouri Geological Survey, with the active help of Dr. H. C. Spicer of the U.S.G.S. who spent much time in instructing the author in both field techniques and interpretation."

REVIEWS

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The Need of a New Philosophy of Prospecting, L. B. Slichter, *Mining Engineering*, Vol. 12, No. 6, June 1960, pp. 570–576.

Louis Slichter possesses an envied reputation as a pioneer in mining geophysics; this reputation certainly is enhanced by his publications in recent years on the application of statistical methods to the planning and execution of exploration campaigns. As a pioneer, in a commerce as basically conservative as the current U. S. mining industry, Dr. Slichter will meet, and surely expects, sharp criticism. At the present it seems likely that the major criticism will arise from the audience to whom Dr. Slichter addressed his 1960 Jackling lecture—the exploration managers of large mining companies. The criticism will perhaps arise through misunderstanding of the main purpose of Dr. Slichter's paper regarding the development of a new *philosophy* of prospecting based upon quantitative statistical analyses of the ore search problem. The misunderstanding is increased by the inclusion in Dr. Slichter's speeches and writings of a short course in probability theory, which should be somewhat beyond the adroit exploration manager who has long since left erudition in favor of economics, politics, and logistics. To reach this audience, Dr. Slichter has a long way to go. For the geophysicist, however, Dr. Slichter has presented food for considerable thought. Most mining geophysicists routinely employ a minor amount of statistics in planning aerial geophysical surveys, but it is questionable whether or not most mining geophysicists have attempted to proceed as far as Dr. Slichter and his followers. They should consider it!

One apparent weakness of Dr. Slichter's present work is the scanty comment on the validity of his basic data. For example, the distributions of "mines" in the Basin and Range region and in the Precambrian outcrop area of Ontario were discussed and illustrated graphically, and yet the definition of a mine as employed is open to serious debate. In some parts of the world a mine is humorously, yet realistically, defined as a headframe with a hole under it. Such neglect of the validity of basic data could lead to additional misunderstanding of Dr. Slichter's purpose.

If one considers a large area, say 125,000 square miles of Basin and Range area, as Slichter has done, divides it into smaller but still substantial units of 1,000 square kilometers each, one can obtain the probability of occurrence of a *known* mine within any one small unit. That one should then say that the probability for oc-

currence of future (i.e., undiscovered) mines will follow the same law is a moot point unless one assumes uniform geologic conditions over the original large area. Most geologists will not agree that such uniformity exists. The presence of known large barren intrusives, for example, obviously reduces to zero the probability of a mine occurrence for one or more unit blocks. Such tempering of rigid statistical approaches by knowledge from other sciences must be employed as Slichter undoubtedly realizes. This observation then leads to the conclusion that every prospector must apply his own weighting to statistical evidence for any one unit. Of a similar tempering nature must be the appreciation that Slichter has analyzed a three-dimensional problem by considering only two dimensions. For the "vertically layered" Precambrian, a plan view of orebody distributions perhaps is adequate, but for orebodies occurring in horizontally-stratified rock (e.g., limestone replacements) it would seem that we should consider individual horizons or groups of horizons.

The exuberant statement, "The statistical evidence here presented indicates that the abundance of undiscovered mines in these (productive) areas so much exceeds the few per 1,000 square kilometers that have already been discovered that these discoveries do not reduce to any appreciable degree the number remaining to be found," must discourage rather than encourage many hard-working prospectors who have thoroughly studied currently productive areas without netting themselves an orebody. Again the need arises for modification of Slichter's relatively simple approach.

The statistical conclusion that broad-scale prospecting should be directed toward finding "the elephants" will draw hearty approval from the more intuitively inclined.

In outlining procedures for optimizing target-finding probability while minimizing costs for either drilling or aerial geophysical prospecting, there is little room for controversy. Slichter's presentation of this topic is as advanced as any. One word of caution appears in order, however. When calculating the ratio of probability of discovery for a given-sized target to cost per line mile for various line spacings, the ultimate conclusion is markedly dependent upon whether one assumes one, two, or more traverses across an anomaly to constitute a discovery. Slichter does not make this point sufficiently clear. Further, one must also keep in mind the objective of the aerial program—to *discover* percentage X of all anomalies of a given size or to *delineate* percentage X of all anomalies of this same size.

The geophysicist undoubtedly will wish to refer to Slichter's earlier paper, "Geophysics Applied to Prospecting for Ores," *Economic Geology*, 50th Anniversary Vol. 1955, for a more intensive treatment of one aspect of the subject. An additional interesting reference is "Optimum Prospecting Plans in Mining Exploration," R. M. Ellis and J. H. Blackwell, GEOPHYSICS, 1959, Vol. 24, pp. 344–358.

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Application of the Gravity Method to Iron Ore Exploration, W. J. Hinze, *Economic Geology*, Vol. 55, No. 3, May 1960, pp. 465–484.

The use of the gravitational method in exploration for and development of iron ore bodies is a relatively straightforward problem for the geophysicist. However, it would seem highly improbable that most geophysicists would be capable of, first, clear evaluation of the advantages and limitations of the method in this application and, second, presentation of his awareness in a form readily absorbed by the non-specialist. Such, nevertheless, is the achievement of the author.

This paper is neither an erudite nor exhaustive presentation of applied gravimetry. It is, however, a very practical resume of the factors which should be considered by the geoscientist when considering application of the gravity method to problems of the iron industry. Although written largely on the basis of the author's extensive experience in the Lake Superior iron ranges, the paper provides a good rule book for those who are concerned with iron ore exploration and development elsewhere.

Density contrasts between rock types, the basis of the gravity method, are shown by illustration and discussion to be a function of porosity and composition. The author's neglect of dead-end pore volume in determining porosities of rocks and ores is a minor omission.

The advantages and limitations cited by the author in the title application of the gravity method are as follows:

(a) Advantages
  (1) Non-magnetic iron ores are readily detected and delineated.
  (2) "Quantitative studies of the physical parameters of an ore body—dimensions, geometry, and iron content—are under some geological conditions more aptly made from the results of a gravity survey than from a magnetic survey."
  (3) Gravity anomalies tend to occur over the center of gravity of the causative body as opposed to a markedly displaced location for many magnetic anomalies.
  (4) Measurement of density is easier and requires less elaborate equipment than measurement of magnetic susceptibility. (This statement appears to represent author opinion rather than fact, necessarily.) The inference is also made that fewer measurements are required of density, as opposed to magnetic susceptibility, to obtain a mean value for a particular geologic unit.
  (5) "Gravity studies are less affected by man made disturbances than are magnetic studies."

(b) Disadvantages
(1) A method which reflects density variations is not as diagnostic as one which reflects variations in magnetic susceptibility for the delineation of magnetic iron ores. On a similar note, quantitative analyses of gravity data frequently are limited because a good estimate cannot be provided of the small percentage changes in density between rock and ore.
(2) Taconite ores frequently contain waste silicate horizons which are not detectable because the densities of waste and ore are almost identical. Basic dikes cutting ore zones present a similar problem.
(3) The effect of bedrock relief often obscures or distorts anomalies due to iron orebodies.
(4) The use of an incorrect mean density in calculating Bouguer and terrain corrections may lead to serious errors in the gravity map.
(5) Detailed terrain corrections, frequently necessary, are expensive and always present some degree of uncertainty where excellent topographic maps are unavailable.
(6) Removal of the regional gravity anomaly is an uncertain process and can lead to grossly erroneous conclusions.
(7) The gravity method lacks resolution when compared with the magnetic method.
(8) Gravity surveys are two to three times more expensive than magnetic surveys.

While the author admits that many of the above advantages and limitations are inherent in the gravity method, he is very careful to point out their special significance in iron exploration. However, he gives only cursory treatment to techniques for evaluating their importance under any given set of conditions. By two very useful graphs, the decrease of anomaly with distance from the disturbing mass is contrasted for the gravity and magnetic methods.

It is unfortunate that the author did not have available for publication more than four brief case histories with which to illustrate his analysis.

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Subsurface Mapping, Margaret S. Bishop, John Wiley & Sons, Inc., New York, 1960, ix+198 pp., $5.75.

Subsurface Mapping describes techniques of structural and stratigraphic mapping but with some discussion of stratigraphic interpretation. The heart of the book and the most useful chapters are 7, 8 and 9.

Chapter 7, *Isopach Maps*, has theoretical illustrations showing migration of axes of subsidence, tilting and erosion, combinations of onlap and offlap in conformable and non-conformable sections and isopach maps in reservoir estimation.

Chapter 8, *Facies Maps*, presents a theoretical data sheet for eleven wells. A series of twelve maps then illustrate ways to depict the lithology by various types of facies maps and thicknesses by isopach and isolith maps.

Chapter 9, *Paleogeographic Maps*, discusses and gives examples of paleogeographic, palinspastic, paleotopographic, paleogeologic, worm's eye, and paleotectonic maps.

Chapter 6, *Structure Maps*, could have been made more complete by mentioning dipmeter surveys and core dips as a source of dip data. The complication introduced by whipped wells also might have been discussed.

This book was written for an undergraduate course at the University of Houston. It would serve as a reference for the beginning geologist or geophysicist as to what type of map would be most effective in study or presentation of a structural or stratigraphic problem. The direct explanation and wealth of illustrations make the book also suitable for those without geologic background.

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The Analysis of Variance, Henry Scheffé, John Wiley & Sons, Inc., New York, 1959, xvi+477 pp., $14.00.

Although analysis of variance is one of the most widely used techniques in statistics, a unified and rigorous presentation has not heretofore appeared. Scheffé's book is a masterful summary not only of what has become standard material, but of topics in which there is at present much research activity. Part I, concerned with models with fixed effects and independent observations of equal variance, covers point estimation, confidence ellipsoids, one-way layouts, two-, three-, and higher-way layouts, incomplete layouts (Latin squares, incomplete blocks, and nested designs), and analysis of covariance. The author considers the theory of this Part to be in fairly permanent form.

Part II deals with random-effects models, mixed models, randomization models, and the effects of departures from the assumptions of normality, independence, and equality of variance of the observations. The corresponding theory is far from complete, and considerable extensions are to be expected.

The appendices include material on vector and matrix algebra (excellent, concise accounts), ellipsoids and their planes of support, noncentral chi-squared variables and noncentral F and t distributions, and multivariate normal distributions. Four sets of tables complete the book: F-tables, Studentized Range Tables, Pearson and Harley Charts for the power of the F-test, and Fox charts for the power of the F-test.

Among topics omitted are multivariate generalizations, sequential methods, nonparametric theory, fractional replication, and response-surface exploration. Only incidental mention is made of design of experiments.

Much of the material has previously not appeared in

book form. A particularly valuable feature is the inclusion of over one hundred problems, none of which can be labeled routine. Scheffé's book is without doubt an outstanding contribution to the statistical literature. Anyone seriously concerned with the subject can do no better than to give this volume a careful and painstaking examination.

H. KAUFMAN
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Statistical Theory of Signal Detection, Carl W. Helstrom, Pergamon Press, New York, 1960, viii+364 pp., $9.50.

In the words of Norbert Wiener, "the whole of engineering is rapidly assuming a statistical aspect." If this is so, it is largely due to Wiener himself who was among the first to recognize that disciplined progress in this direction was being hampered by semantic and conceptual barriers between investigators, who were really working on essentially related phenomena. Thus, the statistician working with parametric models, computing confidence intervals and smoothing various "time series," the mathematician dealing with points in an infinite-dimensional space, with probability measures, Borel fields and deducing abstract theorems concerning "stochastic processes," and finally the engineer plagued with "noise" problems, were all interested in the same phenomenon, but with differing motivations, backgrounds and terminologies.

Ever since the basic and decisive work of Wiener (and Kolmogoroff in Russia) in the early 1940's, the insularity of the three schools has given way to a more cosmopolitan outlook, resulting in incalculable mutual benefits. One example of this is the impressive structure which has come to be known as the statistical communication theory. A very important chapter in this theory, namely, statistical theory of signal detection, forms the basis for the book under consideration.

Opening with an introduction to the theories of linear filtering and random noise, the author next explains the statistical theory of hypothesis testing which he then uses as a framework for treating signal detection as a decision problem. It is further shown how detection systems can be designed to achieve the greatest long-run success and how these systems may be analyzed in terms of false-alarm and detection probabilities. (The designs are mathematical—no hardware is discussed.) Among the other important topics treated, we may mention the statistical theory of estimation as applied to the problem of estimating signal parameters in the presence of random noise, and finally the statistical resolution of overlapping signals.

Though decision-theory methods offer powerful analytical tools capable of yielding many elegant results, these are based primarily upon the concept of a criterion-of-optimality which, in general, lacks the important property of uniqueness. Selection of these criteria or decision rules (essentially, decision rules are transformations which map observation space into decision space) are motivated to a large extent by the observer's judgment and experience, so that the methods used are not entirely non-subjective. Needless to say, different criteria lead to different results.

All of this, of course, is not intended to be a criticism of the author. This reviewer merely wanted to indicate that those who are looking for a cook-book with specific recipes for solving all noise problems, will be disappointed in this book. On the other hand, those who would like to understand and follow the future developments in this exciting field, could profit appreciably by reading this excellent introductory text.

Helstrom's book is written at the graduate level and assumes a proportionate amount of mathematical maturity. Yet, because its style is informal and non-rigorous, the book will appeal primarily to non-mathematicians.

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Magnetic Susceptibility of Some Rock Forming Silicate Minerals Such as Amphiboles, Biotites, Cordierites, and Garnets, Yasuhiko Syono, *Journal of Geomagnetism and Geoelectricity*, Vol. XI, No. 3, 1960, pp. 85–93.

Natural Occurrence of Titanomaghemite and Its Relevance to the Unstable Magnetization of Rocks, Syuniti Akimoto and Ikuo Kushiro, *Journal of Geomagnetism and Geoelectricity*, Vol. XI, No. 3, 1960, pp. 94–110.

Palaeomagnetic and Geologic Researches for the Volcanic Rocks around Lake Suwa—Palaeomagnetic Researches for the Pliocene Volcanic Rocks in Central Japan (2), Kan'ichi Momose, Kunio Kobayashi, and Tetsuo Yamada, *Bulletin of the Earthquake Research Institute*, Vol. 37, Part 3, 1959, pp. 433–481.

Palaeomagnetic Studies on Tertiary and Cretaceous Rocks in Japan, Takesi Nagata, Syun-iti Akimoto, Yoshio Shimizu, Kazuo Kobayashi, and Hisashi Kuno, *Geophysical Notes*, Vol. 12, No. 2, 1959, pp. 378–383.

In the first paper by Yasuhiko Syono, the magnetic properties of some amphiboles, biotites, cordierites, and garnets are presented. The properties determined were the magnetization curve between 0 and 2,000 oersteds at room temperature and also at 90°K., and the susceptibility-temperature curve. The minerals such as garnet, olivine, and pyroxene had susceptibilities that agreed with theoretical values derived from Langevin's equation. The amphiboles, biotites, and cordierites had

susceptibilities greater than the theoretical value. Syono suggests that the increase in susceptibility may indicate a weak interaction or coupling among the magnetic ions through the OH radical or H_2O molecule contained in the mineral crystal structure. This paper adds to the somewhat scarce data on the magnetic properties of the silicate minerals found in common igneous and metamorphic rocks.

The second article, by S. Akimoto and I. Kushiro, also deals with the magnetic properties of certain minerals contained in igneous and metamorphic rocks. They have found from x-ray and chemical analyses that titanomaghemite occurs primarily in those rocks which show unstable remanent magnetization. The titanomaghemite is believed to be derived from the natural oxidation of titanomagnetite. The process of oxidation destroys the thermoremanent magnetization of titanomagnetite. The degree of magnetic instability of the rock appears to be closely associated with the extent of the alteration or oxidation. This paper establishes a criterion whereby rock samples containing titanomaghemite are generally unstable and are unsuitable for palaeomagnetic studies.

The last two papers deal with palaeomagnetic studies on Quaternary, Tertiary, and Cretaceous rocks in Japan. The authors of these papers present data which they interpret as giving support to the hypothesis of polar wandering as proposed by Runcorn. The combined results of these papers indicate that the pole migrated from 42° N–153° W in Middle Cretaceous time to 79° N–57° W in the Upper Pliocene. In addition, K. Momose et al deduced from their measurements that during late Tertiary or early Quaternary the direction of the dipole was reversed and that, while reversed, it migrated in a counterclockwise direction above the present earth's rotation axis. This particular feature of palaeomagnetism was used by Momose et al in an attempt to demonstrate that remanent magnetization direction can be used for stratigraphic correlations in volcanic areas and the interpretation of geomorphological events. Unfortunately, their data possess such variations that its use for detailed deductions does not seem justified as does its use for generalization. For this reason the demonstration is not entirely convincing.

For their palaeomagnetic research on Tertiary and Quaternary rocks in Japan, Nagata et al cite the work of Akimoto and Kushiro as having established a criterion for identifying unsuitable magnetized rock samples. An interesting feature of Nagata's article is an illustration showing the interpreted paths of polar wandering obtained from European, North American, Indian, Australian, and Japanese data. A comparison of the paths shows the pole position to have been displaced farther from the present geographic pole in past geologic periods for all paths, but no two paths coincide. A unique and possibly significant feature is that each path shows that the magnetic pole approached the present geographic pole from the opposite side of the earth from where the samples were acquired. Though the authors express the belief that their work supports polar wandering and possibly continental drift, their illustration gives the impression that the subject of polar wandering will continue to be controversial.

These four Japanese articles, plus many others in the current literature, emphasize the excellent effort which is being applied by the Japanese in the field of rock magnetism.

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Physics of the Upper Atmosphere, edited by J. A. Ratcliffe, Academic Press, New York, 1960, xi+586 pp., $14.50.

The study of upper-atmosphere physics is rapidly advancing and diversified, involving a wide variety of experimental techniques and theoretical concepts. To present a survey of the entire topic that is both up to date and authoritative, Mr. Ratcliffe has enlisted several eminent scholars to write individual chapters on their specialities. On the whole, the finished product is admirable. Anyone who has had a need for S. K. Mitra's treatise on "The Upper Atmosphere" will want to own this volume, which is similar in scope and depth.

Still, the subject is a bit broader now than when Mitra issued his second edition (1952); and a collection of review articles can never quite penetrate as deeply as the full-length monograph. There an author finds space to develop his subject in mathematical and physical detail and has the perspective to tie together all the varied, but related, aspects of his topic. Thus, there is still a need for a modern textbook on the physics of the upper atmosphere—one that will emphasize the fundamental theoretical principles.

One of the most valuable chapters in the volume is the one on "The Ionosphere" by Ratcliffe and K. Weekes. It fills an important gap in the literature, treating all phases of the topic—theory of formation; experiments and their interpretation; and physical properties, morphology, and time variations—with skill and clarity.

D. R. Bates, generally regarded as the dean of aeronomists, has contributed three chapters on the airglow and the aurora with the conservative restraint and lucid authoritativeness we have come to anticipate and admire in his writing

Construction of models (i.e., density, composition, and temperature versus height) of the upper atmosphere is discussed by M. Nicolet. This is a topic currently involving extensive use of rocket and satellite observations but interpretation of these data requires a proper application of theoretical principles and this chapter will

be invaluable to those associated with measurements of atmospheric structure.

Several other excellent chapters appear. For example, E. H. Vestine gives a valuable review of geomagnetic disturbances with emphasis on ionospheric currents. Chapters by H. E. Newell and H. Friedman will be welcomed by those of us who find it difficult to keep up with the direct exploration of the upper atmosphere and the solar spectrum by rockets and satellites.

But it is inevitable, I suppose, that all chapters cannot be of uniformly high quality. Occasionally one sees a review article with an inordinate amount of emphasis on the author's own theories or experiments, or one written with too much slang of the subject, too little consideration for the reader in the borderline fields, and evidently written in too great haste. The research in a subject is too often parroted, too seldom analyzed, too readily summarized, and insufficiently criticized. Conclusions, major and minor, experimental and theoretical are reported without an indication of the basic means of reaching these results.

The author of a review accepts an obligation to learn his subject so well that he writes it with perception and some sensitivity. Invitations to write summary articles are too often accepted as status symbols when the author lacks the necessary obsessive, compulsive desire to review his subject.

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Williams Bay, Wisconsin

Methods in Geochemistry, edited by A. A. Smales and L. R. Wager, Interscience Publishers, Inc., New York, 1960, vii+464 pp., $13.50.

In the last decade or so there have been rapid advances in analytical techniques for determining the elemental constituents of the earth and its parts. Interest has centered particularly on isotopes and elements in low concentrations many of which were difficult if not impossible to determine before the advent of isotope dilution and radiochemical techniques. This book is a compilation of articles by both geologists and chemists utilizing these newer analytical techniques in geochemical research.

The first chapter contains a discussion of sampling procedures and methods of preparing samples for analysis. The handling of rocks, unconsolidated sediments, natural waters, gases, and organic matter are discussed along with special sections on handling such things as soils and meteorites. This is followed by a chapter on classical gravimetric, and volumetric methods of analysis and the more recent colorimetric methods. Succeeding chapters deal with such subjects as spectrochemical analysis, fluorescent X-ray spectrography, stable isotope geochemistry and mass spectrometric analysis, isotope dilution analysis, radiochemical methods, radioactivation analysis, polarography, and some modern chemical separation methods.

Most of the chapters are well written and are accompanied by extensive bibliographies. The book is well suited for students planning to go into the field of geochemistry and those who want an introductory survey of the types of analytical procedures that are available. However, it has two serious drawbacks for the professional geochemist who is interested in an up-to-date survey of the newest procedures.

First, it appears that some of the chapters were written long before the book was published and consequently are considerably out of date. For example, a footnote in Chapter 3 refers to a text on colorimetric determination of non-metals that was published after Chapter 3 was written. This text appeared in 1958. This time lapse is particularly unfortunate in the case of the chapter on Fluorescent X-ray Spectrography since several important developments have taken place since 1957–58. For example, the author discusses a curved transmission-crystal fluorescent X-ray spectrograph manufactured by The General Electric Company. The manufacture of this instrument was discontinued several years ago and has been replaced by the flat reflecting-crystal spectrograph. The author also makes no mention of the gas flow proportional counter, a detector which has extended the useful range of the X-ray spectrograph to the lower atomic number elements such as magnesium and aluminum. These counters were available in 1957. Interscience Publishers, the publishers of "Methods in Geochemistry," also published a book on X-ray spectrochemical analysis by L. S. Birks in 1959 with more up-to-date information. There are practically no references in the bibliographies to work done after 1958 except for a few authors who apparently updated their chapters before going to press.

The second point is that most of the discussion relates to equipment and data available in the United Kingdom. This is understandable since most of the authors are in research organizations in the U.K. However, the reader quickly gets the impression that no special effort was made to obtain up-to-date information from Europe, Russia, or the United States. For example, although the chapter on polarography is a very good introduction to the principles and application of polarography to inorganic ion analysis, the section on instrumentation is far too brief. It fails to mention the many commercially available polarographs both by American and European manufacturers.

In general, the data reported are quite accurate although the authors occasionally get into trouble when making interpretations. For example, the author of the chapter on Radiochemical Methods infers that widely discordant ages obtained by lead isotope methods on the same mineral could be considerably improved by stricter control of the chemical analyses. Actually the

chemistry would need to have fantastic errors to explain some of these discrepancies. Consequently, most people believe that variability in leaching and thermal reworking of the samples causes observed variations. The same author reports the observed disintegration rate of carbon in present day organisms as 16.1 ± 0.8 disintegrations per minute per gram whereas 13 ± 0.5 is the more accepted figure.

In general, the criticisms relate to items of more interest to the professional geochemist than to those chemists or geologists wishing to know more about how analytical data in geochemistry are obtained, or to students in this field. As previously mentioned, the book is well suited for these latter groups.

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Jersey Production Research Company
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PUBLICATIONS RECEIVED

BOOKS

Hydrodynamics of Oceans and Atmosphere, by Carl Eckart, Pergamon Press, New York, $9.00.

Soviet Research in Geophysics, v. 4, American Geophysical Union, Washington, D. C., $7.50.

Space Research, edited by H. K. Kallman, Interscience Publishers, New York, $24.00.

The Exploration of Space, edited by Robert Jastrow, Macmillan Co., New York, $5.50.

Theory of Detonation, by Ia. B. Zeldovich and A. S. Kompaneets, Academic Press, New York, $14.00.

The Physics of Flow Through Porous Media, revised edition by A. E. Scheidegger, Macmillan Co., New York, $15.50.

PERIODICALS

American Journal of Science, v. 258, nos, 8, 9 & 10 (Oct., Nov. & Dec., 1960).

Annali de Geofisica, v. 13, n. 2 (April & June, 1960).

Boletin de la Asociacion Mexicana de Geologos Petroleros, v. 12, nos, 3, 4, 5, & 6 (Mar., Apr., May, & June, 1960).

Bolettino di Geofisica, v. 2, nos. 5, 6, & 7 (March, July, & Sept., 1960).

Bulletin (Izvestiya), nos. 1, 2 & 3 (Jan., Feb. & March, 1960).

Bulletin of the Research Council of Israel, v. 9G, nos. 2 & 3 (August, 1960).

Bulletin of the Seismological Society of America, v. 50, nos. 3 & 4 (July & Oct., 1960).

Deutsche Hydrographische Zeitschrift, v. 13, nos. 3 & 4 (1960).

Economic Geology, v. 55, nos. 6 & 7 (Sept.–Nov., 1960).

Egyptian Journal of Geology, v. 3, n. 1 (1959).

Erdöl und Kohle, v. 13, nos. 8, 9, & 10 (Aug., Sept., & Oct., 1960).

Geophysical Abstracts, v. 181 (April & June, 1960).

Geophysical Notes, v. 13, n. 1 (1960).

Geophysical Prospecting, v. 8, n. 3 (Sept. 1960).

Gerlands Beiträge zur Geophysik, v. 69, n. 4 (1960).

Journal of Geomagnetism and Geoelectricity, v. 11, n. 4 (1960); v. 12, n. 1 (1960).

Journal of Geophysical Research, v. 65, nos. 9, 10 & 11 (Sept., Oct., & Nov., 1960).

Journal of Petroleum Technology, v. 12, n. 9 (1960).

Mines Magazine, v. L, nos. 9, 10 & 11 (Sept., Oct., Nov., 1960).

Mining Engineering, v. 12, nos. 9, 10 & 11 (Sept., Oct., Nov., 1960).

Nachrichten aus dem Karten- und Vermessungswesen, v. 1, n. 15 (1960).

Physics Today, v. 13, nos. 9, 10 & 11 (Sept., Oct., Nov., 1960).

Proceedings of the Cambridge Philosophical Society, v. 56, Part 4 (Oct., 1960).

Quarterly Journal of the Geological Society of London, v. 116, parts 2 & 3, nos. 462 and 463 (Oct., 1960).

Transactions American Geophysical Union, v. 41, n. 3 (Sept., 1960).

Zeitschrift für Geophysik, v. 26, nos. 2 & 3 (1960).

CARL COLQUITT CRENSHAW

The many friends of Carl Colquitt Crenshaw were shocked and saddened to learn that he succumbed to a heart attack on Saturday, September 17, 1960. Carl was born in Lockhart, Texas, January 30, 1913. After graduating from Alvin, Texas, high school, he attended Southern Methodist University where he took general academic courses. He subsequently completed special courses in industrial and economic engineering, industrial labor management, and industrial psychology. Carl started his career with Phillips Petroleum Company in March, 1935, as a surveyor on a seismograph crew, progressing to party manager and assistant manager of the core drills. His work on Company seismograph crews took him to many locations throughout the southern, mid-continent, and northwestern areas of the United States. In July, 1939, he was transferred to the Bartlesville office and made superintendent of core drills. In August, 1950, he was made manager of personnel and equipment, and in September, 1954, he was promoted to Administrative Assistant to the Manager of the Land and Geological Department.

Carl's keen interest in people made him many friends in all walks of life. Strong devotion to his family, faithfulness to his company, love for his work, and loyalty to and pride in men working with him were the dominant factors of his life. He held membership in many societies and clubs, and was a member of the St. Luke's Episcopal Church, Bartlesville, Oklahoma.

Carl is survived by his wife, Dimple, and one daughter, Mrs. Jerry A. Futch, Pasadena, Texas. All his many friends deeply regret his passing.

A. J. HINTZE

FRANK VICTOR HENDRICKSON

On May 13, 1960, "Vic" as he was known by all his friends and associates, passed on from cerebral thrombosis, at St. Luke's Hospital, Houston, Texas, after having been hospitalized five days.

As far back as 1952 Vic had been handicapped by multiple sclerosis, which was a terrible blow to him as he was very athletic and always interested in all sports, and his friends marveled at his courage during this period.

Born in Spickard, Missouri, on November 22, 1901, Vic attended grade school and high school at Okmulgee, Oklahoma, having been very active in sports and, excelling in football, he was awarded an athletic scholarship to West Tennessee Teachers College (now Memphis State). His exploits are fondly remembered by his classmates.

On December 4, 1926, he married Sue Robinson, his high school sweetheart, who gave him encouragement and inspiration throughout his life.

After leaving college he joined a Roxana torsion balance crew at Beaumont, Texas, received his first training under A. Van Weeldon and later did field surveying for Dr. Ott on the Yates field discovery.

Later, he joined Rycade and worked with torsion balance under the supervision of Dr. Donald C. Barton. In 1927 he joined the Vacum Oil Co., as a party chief on their first torsion balance crew. The depression then forced the abandonment of the exploration department and in February 1931 he was transferred to the production department.

Early in 1933 at the encouragement of Dr. Barton, Vic organized Hendrickson Exploration Co., which he operated until 1940. Then with the decreased use of the torsion balance, Vic, not daunted, decided to gain experience and to learn the other phases of exploration such as gravity, and seismograph. He then joined United Geophysical Co. and did work for them in Venezuela and Alaska.

In 1950 he went to Canada as party manager for Geophysical Associates, and in June 1952, he took over the direction of the seismic department of Geophysical Prospecting Co., in Calgary, Alberta. It was the fall of this year that his illness began, and he took sick leave and did not return.

After this time Vic worked as a seismologist for various Houston based firms, including Advanced, National, and Offshore Exploration Group. In 1958, Vic, due to the worsened degree of multiple sclerosis, was forced to retire from active work, and a greater part of these last two years was spent in the hospital.

In his busy and varied life Vic was also active in the St. Mark's Episcopal Church, Society of Exploration Geophysicists, Houston Geophysical Club, Houston Engineer's Club, Registered Geological Engineer State of Texas, and in addition organized and was the first scout master for the troop sponsored by the Men's Club-Southside place, Houston, Texas.

He is survived by his beloved wife Sue, Houston, Texas; son, Frank Victor Jr., and three grandchildren, Frank Victor III, Vivian Sue, and James Beaumont, of Louisville, Ky. A brother, Harry, Trenton, Mo., and a sister Miss Francis Hendrickson, Houston, Texas.

Those of us who were privileged to know him will remember him as a wonderful person.

GEORGE CONWILL

PATENTS

O. F. RITZMANN*

GEOCHEMICAL PROSPECTING

U. S. No. 2,946,657. R. C. Reynolds, Jr. Iss. 7/26/60. App. 3/5/58. Assign. Pan American Petroleum Corp.

Separating Illite for Geochemical Analyses. A method of separating illite from rock samples by disaggregating the mixture by action of supersonic vibration while the mixture is submerged in water, then separating as to particle size, and treating the clay-mineral portion with strong alkali and acids.

GRAVIMETRIC PROSPECTING

U. S. No. 2,949,536. W. G. Langton. Iss. 8/16/60. App. 2/4/57. Assign. U.S.A.

Method and Means for Vertical Attitude Determination. A system for determining the vertical at very high altitudes by optically scanning the horizon and using the modulation of light intensity to control servomotors that orient the scanning axis to reduce the modulation signal.

U. S. No. 2,949,783. N. C. Butler. Iss. 8/23/60. App. 10/28/57. Assign. U.S.A.

Gravity Sensing Device. A device for actuating a contact upon loss of weight of a mass held by two arms arranged to close an electrical contact when the mass loses weight as in free fall.

U. S. No. 2,950,784. K. L. Hertel. Iss. 8/30/60. App. 9/23/55. Assign. University of Tennessee Research Corp.

Instrument Damping Devices. An on-off type of frictional damping device for an instrument that oscillates in a plane, the moving member of the instrument having a fork between whose tines a flexible strand is oscillated in a transverse plane so that the strand alternately contacts the inside surfaces of the tines.

MAGNETIC PROSPECTING

U. S. No. 2,950,433. C. H. Kaplan and J. J. M. Pelen. Iss. 8/23/60. App. 10/22/54 and 10/13/55. Assign. Compagnie pour la Fabrication des Compteurs et Materiel d'Usines a Gaz.

Measuring Device. An automatically compensating magnetometer having saturable core reactors in a bridge circuit with galvanometer balance indicator that controls a condenser feeding amplified a-c to field coils of a d-c generator that supplies measured compensating current to a coil around the saturable cores.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,950,434. F. Haalck. Iss. 8/23/60. App. 8/23/57 and 8/21/58. Assign. Askania-Werke A.G.

Calibration of Torsion Magnetometers. A system for calibrating a suspended magnet magnetometer by manually rotating the instrument so as to cause a known amount of a complementary component to act on the magnet and measuring its deflection.

RADIOACTIVITY PROSPECTING

U. S. No. 2,944,150. F. S. Replogle, Jr. and D. A. Gordon. Iss. 7/5/60. App. 6/17/54. Assign. U.S.A.

Means for Modulating and Detecting Neutron Flux. A slow neutron detector having an ionization chamber surrounded by a boron-containing material to which a pressure wave of sonic frequency is applied, the a-c component of the ionization chamber current being measured.

U. S. No. 2,944,176. N. Anton. Iss. 7/5/60. App. 7/13/53.

Radiation Detector. A radiation detector having a toroidal chamber in a conductive casing with a permeable window coated with a thin conducting layer, the toroid having a central circular electrode with conductive supports for the window.

U. S. No. 2,946,888. S. A. Scherbatskoy. Iss. 7/26/60. App. 5/2/55.

Nuclear Measuring System. A radiation detector having two scintillating crystals arranged so that one surrounds the other and with the phototube outputs fed to a coincidence circuit which adds the pulses.

U. S. No. 2,947,870. J. W. Merritt. Iss. 8/2/60. App. 4/12/55.

Radiation Survey Method. A radioactivity prospecting method in which gamma-ray measurements are made on the surface of the ground and soil samples are taken at each station, the mineral retentivity of each sample being measured in the laboratory and the gamma-ray measurement corrected for soil retentivity.

U. S. No. 2,948,812. H. P. Quinn. Iss. 8/9/60. App. 5/23/57. Assign. Tung-Sol Electric Inc.

Circuit for Geiger Counters. A Geiger counter circuit having a monostable multivibrator connected to a meter and with a gas discharge diode connected across the anode-cathode circuit of the normally conducting multivibrator tube to eliminate pulse variation due to variation in supply voltage.

U. S. No. 2,950,392. F. K. Campbell. Iss. 8/23/60. App. 10/12/56. Assign. One-half to The Moran Corp.

Method of Exploration for Locating Hydrocarbons and Oil. A radioactivity prospecting method in which the indications of a radioactive gas detector, a gamma-ray detector, and a detector of all radiation are separately recorded and compared.

U. S. No. 2,950,393. B. G. Southward. Iss. 8/23/60. App. 11/20/56. Assign. The Bendix Corp.

Gamma Compensated Neutron Detector. A neutron detector having an ionization chamber with a segmented neutron-absorbing shield, one segment being motor-driven and acting as a shutter so that the a-c signal of the ionization chamber is a measure of neutron intensity.

SEISMIC PROSPECTING

U. S. No. 2,944,620. W. J. D. Van Dijck. Iss. 7/12/60. App. 5/4/54 and 5/3/55. Assign. Shell Oil Co.

Method of Recording Seismograms and of Preparing Derived Seismograms. A method of portraying seismograms by filtering the signal through a number of parallel-connected electrical filters whose output signals are used to control mirrors that reflect varying areas of different color light onto a color film so that different frequencies are recorded in different colors.

U. S. No. 2,945,378. R. W. Martin. Iss. 7/19/60. App. 9/13/57. Assign. Physical Measurements Corp.

Linear Accelerometer. A liquid-damped accelerometer whose mass is suspended on diaphragms with a wedge-shaped opening which is partially obstructed by a plate on a bi-metallic arm so as to correct the damping for the effect of temperature on viscosity of the liquid.

U. S. No. 2,945,379. F. R. Barnes and L. R. Greenaway. Iss. 7/19/60. App. 8/25/55. Assign. Boeing Airplane Co.

Accelerometer and Magneto-Resistive Electromechanical Transducer Used Therein. An accelerometer whose suspended system carries a grid of magnetoresistive elements in a bridge circuit between the poles of a permanent magnet.

U. S. No. 2,946,017. F. J. Murphree, Jr. Iss. 7/19/60. App. 12/28/56. Assign. U.S.A.

Automatic Volume Control. An avc system in which a sample of the output signal is amplified, rectified, filtered, and charges a condenser through a non-linear resistor having a negative voltage-resistance characteristic, and the condenser voltage is used to control the amplifier gain.

U. S. No. 2,946,393. J. E. Hawkins. Iss. 7/26/60. App. 6/19/53. Assign. Seismograph Service Corp.

Method of Seismic Prospecting. A seismic profiling system in which the records are corrected for elevation and weathering by adjustment of the reproducing heads and corrected for step-out by means of cams that move the heads during reproduction to correct the records to a common datum plane.

U. S. No. 2,946,643. J. S. Hutchison and A. B. Hildebrandt. Iss. 7/26/60. App. 2/15/56. Assign. Jersey Production Research Co.

Clipped Trace Recording of Electrical Signals. A channelized recording system using a point source between two linear light sources so that small amplitudes are recorded as a variable amplitude trace but large amplitudes are recorded in variable area form.

U. S. No. 2,946,980. R. M. Bridges, E. W. Rudy, and J. A. Rummell. Iss. 7/26/60. App. 5/2/55. Assign. Bendix Aviation Corp.

Sound Ranging System. An underwater echo ranging system using a directional hydrophone as sound generator and receiver, and rotating the hydrophone stepwise into various azimuths and synchronously rotating the sweep of a c-r tube on which the returning signal is displayed.

U. S. No. 2,947,377. R. A. Peterson. Iss. 8/2/60. App. 10/3/52 and 11/29/56. Assign. United Geophysical Corp.

Well-Shooting System. A velocity shooting system in which shots are located at the surface and a pressure-sensitive detector is lowered into the well on a cable to different depths.

U. S. No. 2,947,945. M. J. Relis and W. Yuni. Iss. 8/2/60. App. 11/5/54. Assign. Burroughs Corp.

Time Domain Filter. A filter for eliminating from a train of pulses those pulses that are either shorter or longer than a selected duration.

U. S. No. 2,948,880. R. S. Thatcher. Iss. 8/9/60. App. 5/31/57. Assign. Dresser Industries, Inc.

Apparatus for Producing Seismic Records. An apparatus for correcting a seismogram for normal move-out during re-recording in which the play-back heads are individually moved in the direction of tape movement by means of arms that engage the head-moving slides and which are set to give the proper move-out for shallow reflections and follow the proper geometry to decrease the move-out with increasing time.

U. S. No. 2,949,974. W. Beuermann. Iss. 8/23/60. App. 10/26/55. Assign. Seismos G.m.b.H.

Seismic Exploration Apparatus. A reflection seismograph recording system in which first arrivals are recorded without mixing and at a predetermined time after the shot moment the bias voltage is removed from a mixing tube so that subsequent reflection signals from the geophones are recorded with mixing.

U. S. No. 2,950,459. G. B. Loper and R. R. Pittman. Iss. 8/23/60. App. 8/30/51, 7/9/52, and 10/27/53. Assign. Socony Mobil Oil Co., Inc.

Seismic Record Display and Re-recording. A seismic re-recording system in which the field record is recorded in reproducible form and formed into an endless belt for reproduction on a c-r tube, predetermined portions of the record being selected for display by a timing line counting circuit controlled by the shot moment signal.

See also Patents 2,943,694, 2,944,621, and 2,949,973 listed under WELL LOGGING.

WELL LOGGING

U. S. No. 2,943,397. R. Ring. Iss. 7/5/60. App. 6/21/55. Assign. Sperry-Sun Well Surveying Co.

Bore Hole Surveying Method and Apparatus. A well surveying apparatus having two spaced sets of recording inclinometers so that by operating in steps equal to the spacing it is possible to correct the survey for drift in the orientation gyroscope.

U. S. No. 2,943,546. J. L. Gafford. Iss. 7/5/60. App. 12/29/55.

Shutterless Camera for Taking Pictures of the Wall of a Well or the Like. A strip camera for a borehole in which the film is driven in synchronism with movement of the sonde in the hole and the sonde contains a transverse gyroscope to prevent rotation of the sonde.

U. S. No. 2,943,694. C. Goodman. Iss. 7/5/60. App. 5/17/54. Assign. Schlumberger Well Surveying Corp.

Method and Apparatus for Exploring Boreholes. An acoustic logging system having two transducers on a pad that is pressed against the borehole wall with the transmitter energized with a-c and the receiver connected to a phase detector arranged to sensitize the receiver to shear waves so as to detect fissures and fractures in the borehole wall.

U. S. No. 2,944,148. F. F. Johnson and J. Tittman. Iss. 7/5/60. App. 7/2/54. Assign. Schlumberger Well Surveying Corp.

Apparatus for Investigating Earth Formations. A gamma-gamma logging device having a gamma-ray source and detector in a pad pressed against the borehole wall, the detector being tilted with respect to the vertical axis so that a short face of the pad can conform to the borehole wall.

U. S. No. 2,944,149. G. Herzog. Iss. 7/5/60. App. 8/9/51 and 10/9/56. Assign. Texaco Inc.

Radioactivity Earth Exploration. A gamma-gamma logging device using a gamma-ray source and a short detector having a scintillating crystal, the detector measuring scattered gamma rays over a zone whose axial length is less than one sixth of the distance from the source to the measuring zone.

U. S. No. 2,944,621. R. J. Loofbourrow. Iss. 7/12/60. App. 2/6/56. Assign. Texaco Inc.

Testing Device for Acoustical Logging System. A device that may be placed in contact with an acoustic logging sonde for calibrating the latter and having a detector that picks up the acoustic impulse from the sonde's transmitter and transmits it through adjustable delay lines to two transmitters in contact with the sonde's receivers.

U. S. No. 2,945,129. G. Swift and D. E. Barkalow. Iss. 7/12/60. App. 8/16/56. Assign. Well Surveys, Inc.

Calibrator for Radioactivity Well Logging Instruments. A system for calibrating a well logging sonde that contains a radioactive source by placing the sonde in a tube made of material having a large scattering cross-section so as to return radiation to the sonde and providing an axially movable ring of material having a large capture cross-section between the sonde and the tube.

U. S. No. 2,945,175. E. F. Egan. Iss. 7/12/60. App. 12/21/56. Assign. Texaco Inc.

Electrical Logging System for Exploring Subsurface Formations. A resistivity logging electrode pad carried on a plowshare having a pointed leading edge and a rib with a knife on its leading edge to cut and plow through the mud cake so that the electrodes on the pad contact the formation.

U. S. No. 2,945,952. H. A. Bourne, P. L. Gant, and J. J. Reynolds. Iss. 7/19/60. App. 4/23/56. Assign. Continental Oil Co.

Method and Apparatus for Locating Producing Zones in Wells. A system for analyzing fluid flow into a well by isolating part of the well with two packers and having the fluid entering the zone between the packers flow past a water-soluble radioactive material and then past a radioactivity detector.

U. S. No. 2,946,130. E. L. Groner and L. J. Herndon, Jr. Iss. 7/26/60. App. 3/29/57. Assign. Welex, Inc.

Well Bore Caliper. A calipering device in which the feeler arms are connected by springs to a plate that adds

up the spring forces and transfers them to a single spring whose deflection is recorded.

U. S. No. 2,946,889. N. L. Muench. Iss. 7/26/60. App. 4/15/57. Assign. Jersey Production Research Co.

Focusing System for Use in Radioactivity Well Logging. A radioactivity logging detector using two spaced detectors, the forward one being spherical and the rearward one being annular, with each connected to a discriminator and coincidence circuit so as to count only coincident pulses that produce in the annular detector pulses of Compton-degraded energy.

U. S. No. 2,947,086. W. G. Boyle. Iss. 8/2/60. App. 10/28/58. Assign. Otis Engineering Corp.

Release Assembly for Tubing Caliper. A calipering apparatus in which the feelers are locked by a sleeve having an upward facing flexible cup so that release is effected by inertia of the well fluid when the apparatus is first pulled upward but the cup rolls over to prevent subsequent swabbing of fluid.

U. S. No. 2,947,359. V. A. Josendal and R. J. Stegemeier. Iss. 8/2/60. App. 4/8/57. Assign. Union Oil Co. of Calif.

Method and Apparatus for Determining Direction of Fluid Flow in Boreholes. A system for determining the lateral direction of fluid flow in the formation penetrated by a borehole in which an annular distribution of soluble radioactive material in a porous carrier is placed in the formation and the azimuthal variation in radioactivity is measured on the axis of the borehole after a lapse of time.

U. S. No. 2,947,869. E. F. Egan, G. Herzog, and A. S. McKay. Iss. 8/2/60. App. 10/22/54. Assign. Texaco Inc.

Method of Studying Subsurface Formations. A method of obtaining an injection profile of a well by pumping similar fluids down the tubing to the bottom of the well and down the annulus, varying the relative rates of injection, and observing changes in the level of the interface by adding to one fluid a neutron reactive material so that the interface can be detected by a neutron log through the tubing.

U. S. No. 2,948,810. R. L. Caldwell and S. E. Turner. Iss. 8/9/60. App. 10/25/54. Assign. Socony Mobil Oil Co., Inc.

Delayed Gamma Radiation Log of Oxygen. A radioactivity logging system in which the formations are bombarded with high energy neutrons to activate oxygen to nitrogen-16 and the logging rate and the source-detector spacing are arranged to measure gamma radiation from decay of the nitrogen-16.

U. S. No. 2,948,811. T. W. Bonner and R. L. Caldwell. Iss. 8/9/60. App. 11/8/54. Assign. Socony Mobil Oil Co., Inc.

Neutron Production by Alpha Disintegration of Boron 10. A carbon logging system using a neutron source made by mixing polonium or plutonium with boron highly enriched in B10, the source being surrounded with a gamma-ray shield, and using a detector of prompt 4.8 mev. gamma-rays from carbon.

U. S. No. 2,948,846. M. A. Coufleau. Iss. 8/9/60. App. 11/1/56. Assign. Schlumberger Well Surveying Corp.

Well Logging Systems. An induction logging system using a pulsed sinusoidal excitation and measuring the conductive component of the induced pulse at the instant when the potential applied to the transmitter coil passes through zero.

U. S. No. 2,948,847. F. Bravenec and R. H. Huddleston, Jr. Iss. 8/9/60. App. 5/3/57. Assign. Welex, Inc.

Electromagnetic Conductivity Detection. An induction logging system in which the in-phase component of the induced signal is used to modulate the center frequency of an f-m transmission system.

U. S. No. 2,949,534. A. H. Youmans. Iss. 8/16/60. App. 4/15/57. Assign. Well Surveys, Inc.

High Temperature Scintillation Detector. A thermally insulated scintillation detector in which the photomultiplier tube is inside the insulation and the phosphor is outside and the light passes through a window of low thermal conductivity in the insulation.

U. S. No. 2,949,535. S. A. Scherbatskoy. Iss. 8/16/60. App. 2/9/55. Assign. PGAC Development Co.

Nuclear Well Logging Method and Apparatus. A radioactivity logging system using a neutron source and separately detecting and recording gamma rays of about 7 mev., neutrons of energy below 10 ev., and natural gamma-ray activity, a comparison of the intensities being made to locate trace elements indicative of oil.

U. S. No. 2,949,973. R. A. Broding, J. O. Ely, and G. C. Summers. Iss. 8/23/60. App. 7/27/53. Assign. Socony Mobil Oil Co., Inc.

Methods of and Means for Measuring Travel Times Through Earth Formations. An acoustic logging system in which high frequency timing pulses are counted during the travel of an acoustic pulse from a transmitter and receiver in the sonde, and the count is sampled each foot of vertical movement of the sonde and the samples integrated to give the total travel time.

U. S. No. 2,950,538. A. H. Brandon. Iss. 8/30/60. App. 4/3/58.

Tubing Caliper. A calipering apparatus whose feeler

arms actuate bell cranks that control the position of a push rod that contacts electrical contacts connected through different resistances for determining the position of the push rod.

U. S. No. 2,951,198. A. Blanchard. Iss. 8/30/60. App. 5/17/54. Assign. Schlumberger Well Surveying Corp.

Well Logging Method and Apparatus. Apparatus for locating points of water entry in an oil well having a motor-driven screw impeller that emulsifies the water and drives well fluid past the plates of a condenser in the tank circuit of an oscillator whose frequency is indicated at the surface.

See also Patents 2,944,150, 2,946,888, and 2,950,393 listed under RADIOACTIVITY PROSPECTING.

MISCELLANEOUS

U. S. No. 2,946,625. J. P. Crain and A. H. Crain. Iss. 7/26/60. App. 2/13/59.

Wheel for Marsh Vehicle. A marsh buggy wheel having a hub with side plates with staggered equally spaced arcuate recesses connected by spiral flutes.

U. S. No. 2,946,926. M. M. Hawthorne. Iss. 7/26/60. App. 3/6/58. Assign. Go Oil Well Services, Inc.

Bore Hole Detector and Firing Apparatus. A combined magnetic casing-collar locator and casing perforator in which the collar signal is induced in a high-impedance primary of a transfermer located between two permanent magnets, the transformer also having a low-impedance secondary connected to the perforator so that the latter may be fired by an impulse applied from the surface through the transformer primary.

U. S. No. 2,947,984. C. E. Hastings. Iss. 8/2/60. App. 3/22/57.

Radio Position Determining System. A heterodyne phase-comparison radio location system using three stations each with a transmitter and receiver and with the respective signals heterodyned to give a combination of circular, elliptical, and hyperbolic range patterns.

U. S. No. 2,949,766. D. Kirkham and B. L. Grover. Iss. 8/23/60. App. 3/23/55. Assign. Iowa State College Research Foundation, Inc.

Apparatus for Measuring Fluid Permeability of Porous Materials. A device for measuring the rate of air flow into a permeable material and having a graduated inverted cup that fits into an annular liquid-filled tank whose central opening is connected with a restricted area of the material, the rate of fall of the cup being measured.

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* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

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JOHN C. BEHRENDT

JOHN C. BEHRENDT received a B.S. degree (physics) in 1954 and an M.S. (geology) in 1956, both from the University of Wisconsin. He has spent several seasons doing regional magnetic work in the western United States and Alaska. In 1956 he participated in a glaciological research project on the Juneau Ice Field. Mr. Behrendt served as seismologist on the IGY Antarctic oversnow traverse from Ellsworth Station in 1957–58. Returning to the University of Wisconsin as a project associate on the staff of the Geophysical and Polar Research Center, he has subsequently spent three austral summer field seasons in Antarctica in addition to working on the world regional gravity program.

JOSEPH W. BERG, JR.

JOSEPH W. BERG, JR., a native of Pennsylvania, received his B.S. in mathematics and physics at the University of Georgia and his M.S. and Ph.D. in geophysics at Pennsylvania State University.

He taught mathematics and physics at Armstrong College from 1948 to 1949. He was in charge of geophysics during 1954 and 1955 at The University of Tulsa, and is presently assistant professor of geophysics at the University of Utah.

His professional affiliations are Sigma Pi Sigma, Sigma Xi, American Geophysical Union, Society of Exploration Geophysicists, and Seismological Society of America.

KENNETH L. COOK

KENNETH L. COOK received a B.S. degree in Physics in 1939 from the Massachusetts Institute of Technology. During the next four years, he continued his studies in geology and physics at the University of Chicago, at the same time engaging in part-time teaching duties as a University Fellow and, during the last two years of attendance, as Instructor. Also, he taught a course in Geophysical Exploration for Oil at the University of Chicago in 1941. In 1943 he received a Joint Ph.D. degree in Geology and Physics from the University of Chicago. During 1943 to 1956 he was actively engaged in geophysical field work as geophysicist in the Division of Geophysical Exploration of the U. S. Bureau of Mines (1943 to 1946) and in the Geophysics Branch of the U. S. Geological Survey (1946–1953 full-time; 1953-56 part-time). This field work comprised chiefly strategic-mineral investigations in mining districts of the West in which he employed magnetic, gravitational, electrical (surface and well-logging), and refraction seismic surveys as guides in the exploration. He also made regional gravity surveys in parts of Mary-

land, Oklahoma, Kansas and Utah; resistivity surveys in the Tri-State zinc and lead mining district, and magnetic surveys in Kansas. Since 1952 he has been Professor and Head, Department of Geophysics, University of Utah. His current research interests include regional gravity surveys in Utah to determine major crustal structures; studies of blasts to determine the layering of the earth's crust; and laboratory studies of the propagation of seismic waves through rocks.

He is a member of the American Geophysical Union, American Association of Petroleum Geologists, American Institute of Mining, Metallurgical, and Petroleum Engineers, Geological Society of America, Seismological Society of America, Sigma Xi, and Society of Exploration Geophysicists. He has been active on various committees in both the AIME and SEG. In the SEG he has been a member of the Reviews Committee (1949–53) and the Geophysical Activities Committee (1954–59). He is currently First Vice-President of the Utah Geophysical Society, a local chapter of the SEG. He compiled the subject index of the SEG Cumulative Index published in 1955.

PETER E. GRETENER

PETER E. GRETENER was born in 1926 in Berne, Switzerland. In 1949 he received the diploma as a petrographer from the Swiss Federal Institute of Technology in Zurich. In 1953 he obtained his doctorate in geophysics from the same school upon completion of a thesis dealing with gravity measurements and their interpretation on the Swiss Plateau. He spent the following year at the Geophysics Laboratory of the University of Toronto working on age determinations. Since 1954 he has been employed by the Shell Oil Company of Canada as a geophysicist and field geologist. Dr. Gretener is a member of the European Association of Exploration Geophysicists, the American Geophysical Union, the Canadian Society of Exploration Geophysicists, the Alberta Society of Petroleum Geologists and the Geological Society of Switzerland.

MARTIN F. KANE

MARTIN F. KANE received his Certificate in Engineering in 1950 and his B.Sc. in Geology in 1951 from St. Francis Xavier University, Nova Scotia. From June 1951 to April 1952 he was employed as mechanical engineer with the Department of Navy at the Portsmouth Naval Shipyard, Portsmouth, New Hampshire. In 1952, Mr. Kane joined the Geophysics Branch of the U. S. Geological Survey and since 1954 has specialized in gravity studies in the western United States, Cuba, and New England. He is a member of SEG, GSA, AGU, and the Geological Society of Washington.

L. S. MORRISON

L. S. MORRISON entered Whittier College, Whittier, Calif. in 1946 after serving over three years in the U. S. Army Air Corps. He graduated in 1950 with a B.A. de-

gree in Physics. In 1952 he graduated from The Colorado School of Mines with a Master of Science degree in Geophysical Engineering. From 1952 to 1957 he worked as a geophysicist in the Los Angeles office of Humble Oil and Refining Co. In March of 1957 he was transferred to The Carter Oil Co. as a staff geophysicist in the Tulsa office where he was placed in charge of electronic data processing in geophysics.

He has served as Editor for the Los Angeles area for the Pacific Coast SEG Digest and was Vice-President for the southern section of The Pacific Coast Society of the SEG.

LOUIS C. PAKISER, JR.

LOUIS C. PAKISER, JR., received the degree of Geological Engineer from the Colorado School of Mines in 1942. He served as Junior Geophysicist with The Carter Oil Company from 1942 to 1943 and Geophysical Computer from 1946 to 1949. He was on military leave from 1943 to 1945, serving in an Army topographic mapping unit. In 1949 he accepted the position of National Executive Director of the American Veterans Committee and served in that capacity until 1952. Mr. Pakiser has been serving as a Geophysicist with the U. S. Geological Survey since 1952, with whom he is now Chief of the newly-established Crustal Studies program with headquarters in Denver, Colorado.

Mr. Pakiser has been doing graduate work in geophysics at Stanford University from 1957 to present, and graduate work in applied mathematics at the University of Colorado from 1958 to present.

Mr. Pakiser is a member of the Society of Exploration Geophysicists, American Geophysical Union, Seismological Society of America, Geological Society of America, European Association of Exploration Geophysicists, and the American Association of Petroleum Geologists.

DAVID S. SEABROOKE

DAVID S. SEABROOKE was born in Leeds, England in 1924. He received his B.Sc. (Hens.) degree in electrical engineering from Leeds University in 1945. A year later he joined Seismograph Service Ltd. as seismic observer in Trinidad, B.W.I. He returned to Trinidad in 1948 as seismologist with Weiss Geophysical Co. and was promoted to party chief the following year. Mr. Seabrooke has worked in South Africa, Middle East, West Indies and Canada in both petroleum and mining exploration.

In 1951 he joined Seaboard Oil Co. as review geophysicist in Alberta, Canada. A year later he accepted a similar position with Dominion Oil Ltd. (Standard of California) in Port of Spain, Trinidad, becoming Geophysical Supervisor in 1954 in charge of offshore operations. In 1958 he was transferred to Cochabamba, Bolivia as Senior Geophysicist of Bolivia California Petroleum Co., a subsidiary of California Exploration Co. (Standard of California).

Mr. Seabrooke is a member of the S.E.G. and E.A.E.G.

CHARLES W. TITTLE received a B.S. degree in 1939 and an M.S. degree in 1940, both from North Texas State College. The undergraduate fields of study were physics and chemistry, and the master's degree was in chemistry. He received the degree of Ph.D. in physics from the Massachusetts Institute of Technology in 1948. He held the Gulf Oil Corporation Fellowship in physics at MIT from 1945 to 1948, and prior to that time served as a second lieutenant in the Signal Corps of the Army of the United States. He has had nine years of teaching experience in physics, electronics, and nuclear engineering at North Texas State College, MIT Radar School, and Southern Methodist University, and a total of seven years of industrial research and ad-

CHARLES W. TITTLE

ministrative work involving applied nuclear physics at Gulf Research & Development Company and Tracerlab, Inc. For a number of years he has acted as a private consultant. He is author or co-author of twelve technical papers and was elected a Classic Author of GEOPHYSICS in 1960. He has received a number of patents, mostly in nuclear well logging. He is a member of the American Physical Society, the Institute of Radio Engineers, the American Nuclear Society, the Society of Petroleum Engineers of AIME, Sigma Xi, Sigma Tau, and Pi Tau Sigma. Dr. Tittle took up his current duties as Professor of Nuclear Engineering at Southern Methodist University in 1957.

ANDRIS VIKSNE

ANDRIS VIKSNE was born in Riga, Latvia in 1934, but has lived in the United States since 1950. He received an A.B. degree in Geological Sciences from Harvard University in 1956. In 1958 he received a M.S. degree in geophysics from the University of Utah.

He spent the summer of 1958 as a Geophysicist at the New Mexico Institute of Mining & Technology and did work in the fields of gravity and induced polarization. Since 1959 he has been employed by Texaco Inc. as a seismic computer.

He is a member of the Society of Exploration Geophysicists, Sigma Xi, American Geophysical Union, Seismological Society of America, Mineralogical Society of America, and American Association for the Advancement of Science.

ROBERT J. WATSON

ROBERT J. WATSON was graduated from the University of Toronto in 1925 with a B.A. in Geology, followed by an M.A. in 1926. Field experience in Precambrian geology, further graduate studies in geology, physics and mathematics at California Institute of Technology and the University of Colorado, instructing in geology and geophysics and a year of field research in electrical methods led to a Ph.D. at the University of Colorado in 1933.

Joining the Carter Oil Company in 1936, Dr. Watson has continued with Jersey Standard Companies. In 1939–40 he supervised and interpreted magnetic and gravity surveys for Standard Oil Co. of Egypt and from 1946–48 he was Exploration Manager for Standard Oil Co. (Bahamas) Ltd. He is now with Humble Oil & Refining Co. (Carter Division) and as Senior Geophysicist continues to be associated with magnetic and gravity exploration both for Humble and Jersey's foreign affiliates.

Dr. Watson is a member of the Society of Exploration Geophysicists, the American Geophysical Union and the Geophysical Society of Tulsa.

GEORGE P. WOOLLARD

S. H. YUNGUL

GEORGE P. WOOLLARD received his B.S. (Civil Engr.) from Georgia Inst. Technology in 1937, an M.S. (Geological Eng.) in 1934, the M.A. (Geology) from Princeton University in 1935, and the Ph.D. (Structural Geology) from Princeton University in 1937. He did post doctorate work in geophysics at Lehigh University in 1938–39. He has been a Professor of Geophysics at the University of Wisconsin since 1951.

Since 1948, he has been Chairman of the Special Committee for the Geological and Geophysical Study of the Continents of the American Geophysical Union and past director of the American Geological Institute, Trustee of the Bermuda Biological Station for Research, consultant to the Mapping and Charting Laboratory of Ohio State University, member of the advisory committee to the Office of Naval Research and review panel for Fulbright Fellowships, U. S. National Committee for the International Geophysical Year Technical Panel on Gravity and Seismological Measurements, Space Science Board.

S. H. YUNGUL was born in Istanbul, Turkey, in 1919. He attended the *Mathématiques Speciales* school in Tours, France, in 1938–1939, where he was awarded the mathematics prize. He received his B.S. in Mining Engineering from the Montana School of Mines in 1943, his M.S. in Geological Sciences (Geophysics) in 1944 and the degree of Geophysical Engineer in 1945, both from the California Institute of Technology.

He was employed from 1945 to 1952 by M.T.A. Enstitusu of Turkey, as party chief, supervisor and chief geophysicist, from 1952 to 1955 by Etibank of Turkey as chief geophysicist. He joined California Research Corporation, in 1955, where he holds the position of senior research geophysicist, and is, at present, with A. and M. College of Texas, on a leave of absence from C.R.C.

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with By-laws, Article III, Section 4. References are listed in parentheses following the names of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

APPLICATIONS FOR TRANSFER TO ACTIVE MEMBERSHIP

W. C. Abbott (Ralph C. Cole, R. J. Graf, O. G. Holecamp, Glen Robertson)

Richard P. Barnes (E. L. Wells, W. B. Goodenow, L. E. Whitehead, Frank Searcy)

James R. Bingel (W. E. Heinrichs, R. C. Holmer, G. R. Rogers, J. C. Hollister)

J. S. Blankenship, Jr. (J. M. Kendall, Merrill Smith, A. M. Knouse, R. O. Beightal)

Verlon Boysen (Louis Poindexter, W. B. Lee, W. T. Lea, Don Melton)

Wm. R. Brown, (J. A. Harris, Alvin F. Barker, Irvin B. Murray, Jr., Emory V. Dedman)

Tomas E. Bullock (R. A. Patterson, Flint H. Agee, Frank Press, C. W. Schmidt)

Robert H. Carlyle (R. B. Ross, R. J. Copeland, H. J. McGrew, M. B. Dobrin)

Frank Clynch (Frank Searcy, J. M. Crawford, W. E. N. Doty, L. E. Whitehead)

Robert L. Comer (J. J. S. Hamilton, W. G. Smith, A. A. Dame)

Gunter Wm. Conrad (C. N. Page, C. J. Lomax, A. E. McKay, W. A. Seal, Jr.)

Charles W. Dick (Booth B. Strange, Neal P. Cramer, Charles W. Nicholls)

Wm. H. Diment, (J. R. Balsley, R. J. Bean, H. R. Joesting, Isidore Zietz)

Julius P. Edge (I. L. Nash, J. N. Wilson, J. E. Dorris, Bill Baugh)

C. W. Faessler (E. B. Nichols, D. G. McKay, Harold D. Seigel)

James F. Farley (Karl Dyke, M. B. Widess, H. F. Patterson, J. D. Novotny)

John E. Feather (W. T. Lea, J. M. Holmberg, J. M. Armstrong, John Clements)

Robert O. Harlow (L. G. Morris, G. E. Blackledge, J. G. Jackson, N. K. Moody)

J. O. Hilburn (Karl Dyke, H. F. Patterson, J. D. Novotny, H. K. Richardson)

Edward Johnston, Jr. (K. E. Burg, M. E. Trostle, M. D. Gontarek, C. E. Allen)

Milton H. Lea (P. C. Cook, F. W. Bohanan, B. J. Eubank, R. S. Majure)

Robert J. MacGregor (J. A. Hafer, R. J. Copeland A. H. McKee, H. J. McGrew)

Harold A. Mayfield (G. O. Morgan, J. B. Meitzen, L. A. Markley, Max Walthall)

Harold R. McCormack (R. J. Koenig, J. Swistek, J. A. MacMillan, J. J. O'Bertos)

Edw. F. Murray, Jr. (T. O. Hall, Chester Sappington, Henry Werth, S. W. Tift)

J. V. S. Narayana (A. A. Fitch, T. E. Edwards, J. K. Smith, G. L. Bennett)

Frederick D. Nichol (Andre Farando, E. H. Hume, Michel Gallinaro)

Graves E. Noble (A. W. Musgrave, R. N. Gsell, G. W. Isensee, W. E. Jackson)

John J. O'Bertos (H. R. McCormack, R. J. Koenig, J. MacMillan, J. Swistek)

Chas. B. Officer (M. Ewing, J. B. Hersey, J. L. Worzel, J. W. Berg)

Glenn Robertson (G. H. Samuels, O. G. Holekamp, C. H. Gregory, F. W. Oudt)

Stephen R. Rokke (K. E. Burg, R. D. Everett, R. H. Rainey, J. F. Stephens)

Amalendu Roy (P. K. B. Charua, D. K. Ganguly, T. C. Bagchi, S. N. Gupta)

Daniel Schwartz (T. J. O'Donnell, L. W. Gardner, James Affleck)

Howard A. Slack (Isidore Zietz, H. O. Seigel, S. H. Ward, D. J. Salt)

A. K. Spence (R. F. Zimmerly. E. G. Haines, H. R. Rendeu, R. M. Tready)

David J. Stuart (L. C. Pakiser, R. M. Hazelwood, R. A. Black, W. H. Jackson)

Stanislaw Tokarski, (H. J. McGrew, Jim Hafer, Gordon Hollingshead, A. H. McGee)

Bruce C. Wentner (E. J. Stulken, R. C. Dunlap, Jr., R. D. Everett, B. F. Giles)

APPLICATION FOR ACTIVE MEMBERSHIP

Charles E. Carlberg (T. R. Warrick, L. C. Nelson, L. F. Kehneman, Jr.)

Wm. Harry Clark (G. Reimpel, R. J. Biley, J. E. Procter, R. D. Featherstonhaven)

Lloyd G. Lantinga (M. W. Dewis, A. E. Pallister, C. D. Nelson, G. R. Ham)

Wm. Bennett Moody, (W. H. Reese, L. J. Waddell, C. H. Elliott, G. L. Laird)

James A. Nelson (Wm. H. Adamson, Jr., C. N. Page, B. F. Owings, L. O. Dawson)

Frank N. Tullos (F. J. Feagin, W. D. Mounce, D. H. Gardner, Miss Mona Guiler)

Howard E. Turner (R. W. Upshaw, R. E. Butler, G. M. Mace, Jr., R. P. Clark)

George H. Warburton (S. R. Marsh, E. J. Laurent, H. J. Yorston, E. L. Tomlin)

ANNOUNCEMENTS

31ST ANNUAL INTERNATIONAL MEETING SOCIETY OF EXPLORATION GEOPHYSICSTS
NOVEMBER 5–9, 1961, DENVER HILTON HOTEL, DENVER, COLORADO
THEME: EXPLORATION IN A CHANGING WORLD

General Chairman:	Ralph C. Holmer, Bear Creek Mining Company, 516 Acoma Street, Denver 4, Colorado	AM 6-2141
Vice-Chairman, Finance:	C. L. Barker, E. I. DuPont Company, 922 Midland Savings Building, Denver, Colorado	MA 3-1253
Technical Program:	J. E. White, The Ohio Oil Company Box 269, Littleton, Colorado	PY 4-2601
Exhibits:	Franklin H. Persse, Hercules Powder Company 3062 South Steele, Denver, Colorado	SK 6-8779
Housing:	Charles E. McMunn, Tower Exploration, Inc., 3600 South Huron Street, Denver, Colorado	SU 9-2527
Publicity:	Milton H. Collum, Petroleum Geophysical Company 2011 Glenarm Place, Denver, Colorado	KE 4-0253
Publications:	James E. Thompson, Sun Oil Company, Box 1798, Denver, Colorado	AM 6-2181
Registration:	Arthur W. Black, Continental Oil Company 1041 Continental Oil Building, Denver, Colorado	CH 4-4311
Arrangements:	Wendell H. Merrill, Trans-Con Exploration, Inc. 1700 Broadway, Denver, Colorado	AM 6-3161
Transportation:	Kenneth R. Wells, General Geophysical Company	FL 5-5969
Entertainment:	G. J. Petsoff, Forest Oil Corporation 1610 Denver Club Building, Denver, Colorado	AM 6-2651

SEG MIDWESTERN EXPLORATION MEETING, OKLAHOMA CITY, OKLAHOMA
APRIL 9, 10, & 11, 1961, SKIRVIN HOTEL

PROGRAM:	John Bemrose	Sohio Oil	CE 5-7571
Technical Program	Robert H. Peacock	Superior Oil	CE 2-6306
Meeting Arrangements	D. Ray Dobyns	Mobil Oil	CE 2-7191
Publicity	Harry R. Imle	Humble O&R, Carter Div.	JA 5-5451
ARRANGEMENTS:	Kenneth R. Gilleland	Pasotex Petr.	CE 5-8551
Housing	Elmer A. Opfer	Seis-Tech	CE 2-7579
Registration	John V. Franklin	Atlantic Refining Co.	JA 5-3361
FINANCE:	Charles E. Davis	Pan American Petr.	CE 2-6381
Advertising Sales	Michael Flynn	Tennessee Gas Trans.	CE 5-4471
Program Printing	H. Carroll Talley	Sohio Oil	CE 5-7571
Entertainment	Harry R. DeVinna	Central Exploration	JA 5-5511
SUPERNUMERARY:	A. Jack Oden	Mobil Oil	CE 2-7191
	Ben W. Smith	Conoco	CE 2-1371
	Charles L. Howell	Sohio Oil	CE 5-7571
	Colin Campbell	SEG, Tulsa	GI 7-4438

SPECIAL VOLUME ON ENGINEERING GEOPHYSICS

"The Editor is privileged to designate the February, 1962 number as a special issue on Engineering Geophysics and to have Dr. Charles L. Drake of the Lamont Geological Observatory, Palisades, New York, agree to serve as Special Editor for this volume. Dr. Drake has been fortunate to secure the services of Dr. Howard Pincus of The Ohio State University and Dr. James Gould, Moran, Proctor, Mueser, and Rutledge, to assist him in the development and preparation of this publication.

"The special issue will afford an excellent opportunity

GEOPHYSICISTS NAME 1960–1961 OFFICERS

The Southwest Louisiana Geophysical Society of Lafayette, Louisiana, recently elected new officers. From left to right: (seated) Charles B. Vidrine, 2nd Vice-President; Glynn Schuchardt, President; Bill Flowers, 1st Vice-President; (standing) John Murphy, Secretary; Dick Hollenbaugh, Past President; Glen Hunter, Treasurer.

for creating interest in an important and one of the newer fields of geophysics by collating informative papers. It is hoped that the papers will cover both the theoretical aspects peculiar to this division of geophysics and excellent case histories illustrating this method. The entire profession is encouraged to begin immediately to send manuscripts to Dr. Drake for his consideration."

SPECIAL VOLUME ON MINING GEOPHYSICS

At the 30th Annual Meeting of the Society of Exploration Geophysicists held in Galveston, Texas, the Executive Committee and the Council approved the publication of a special volume on mining geophysics. Editor of the new volume will be Ralph C. Holmer. Stanley H. Ward, H. V. W. Donohoo, and G. R. Rogers will serve as associate editors. July 1, 1963 has been set as the date of publication.

The volume will cover the main geophysical methods employed in mineral exploration. Basic theory, physical property tabulations, results of model studies, and interpretation techniques will be included—illustrated by field results and case histories. The philosophy and economics of mineral exploration will be emphasized.

RALPH HOLMER

ASSOCIATE EDITOR RESIGNS

The Editor regretfully announces the resignation of Mr. Turner L. Kunkel as an Associate Editor due to his new duties as Division Manager, Domestic Producing Department, Los Angeles Division, Texaco, Inc.

FRANKLIN INSTITUTE AWARDS JOHN PRICE WETHERILL MEDAL

MR. VICTOR VACQUIER, Research Geophysicist, Scripps Institution of Oceanography, University of California, LaJolla, Calif., was recognized for "his important invention of the sensitive saturating core magnetometer element, and his development of the first practical airborne magnetometer, providing the fundamental principles which are basic to the later developments."

Mr. Vacquier was born in 1907 in Leningrad, Russia. He received his Bachelor of Science degree from the University of Wisconsin in 1927, and his Master of Arts in 1928. For two years he taught Physics at Wisconsin. In 1930, Mr. Vacquier joined the Gulf Research and Development Company as a geophysicist. While working at Gulf, Mr. Vacquier developed his airborne magnetometer for which he was granted a patent in 1946.

VICTOR VACQUIER

In 1942, Mr. Vacquier joined Airborne Instruments Laboratory at Columbia University. From 1944 to 1953 he was Marine Instruments Engineer with Sperry Gyroscope Company. Then he became a Principal Geophysicist and Professor of Geophysics at New Mexico Institute of Mining and Technology.

In 1957, Mr. Vacquier joined the Marine Physical Laboratory of The University of California's Scripps Institution of Oceanography as a Research Geophysicist. A participant in several of Scripp's long expeditions in the Pacific, Mr. Vacquier's present principal scientific interest is geomagnetism.

Mr. Vacquier is a member of the Geophysical Union, the Geological Society of America, and the Society of Exploration Geophysicists.

AIME ELECTS OFFICERS

The American Institute of Mining, Metallurgical, and Petroleum Engineers has elected Ronald R. McNaughton, of Trail, British Columbia, as President for 1961.

Mr. McNaughton, will take office on Feb. 28, 1961, during The Institute's Annual Meeting in St. Louis. He is Manager of the Metallurgical Division of The Consolidated Mining and Smelting Co. of Canada, Ltd. Mr. McNaughton will succeed Dr. Joseph L. Gillson, of Wilmington, Del., who continues as President of AIME until Feb. 28. Dr. Gillson formerly was Chief Geologist of E.I. du Pont de Nemours & Co.

Lloyd E. Elkins, of Tulsa, production research director for the Pan American Petroleum Corp., will become the AIME President-elect in February, pointing toward his election as President for 1962, following Mr. McNaughton's term.

"EXPLORATION GEOPHYSICS—TODAY AND TOMORROW"

The Canadian Society of Exploration Geophysicists will sponsor a Conference to be held in the *Palliser Room, Palliser Hotel, Calgary, Alberta* on *February 27, 1961*. The program, with the speakers confirmed to date, is as follows:

Economic Aspects

Influence of World Oil Reserves on Exploration Economics

Invitation pending

Economics of Geophysics in Oil Exploration
Paul L. Lyons, Chief Geophysicist, Sinclair Oil and Gas Co., Tulsa, Okla.

Trends and Prospects in Mining and Engineering Geophysics
Norman R. Paterson, Chief Geophysicist, Hunting Survey Corp., Ltd., Toronto, Ont.

Problems of the Geophysical Contractor
Charles M. Moore, Vice President, Geophysical Services Inc., Dallas, Texas.

Geophysics' Share of Todays Exploration Dollar
Invitation pending

Technical Aspects

Technical Limitations of Present Geophysical Tools
W. T. Born, Director of Laboratories, Geophysical Research Corp., Amerada Petroleum Corp., Tulsa, Okla.

Current Research to Improve Effectiveness of Standard Geophysical Methods
F. A. Van Melle, Research Seismologist, Shell Development Co., Houston, Texas.

Status of Direct Oil Finding Methods (Geochemical, Electrical, etc.)
Invitation pending

Personnel Problems

Statistics on Employment of Exploration Geophysicists
Colin C. Campbell, Business Manager, Society of Exploration Geophysicists, Tulsa, Okla.

Alternative Employment for Geophysicists in the Oil Industry
D. C. Jones, Vice-President for Production, Hudson's Bay Oil and Gas Co., Calgary, Alta.

Impact of the Present Slump on Geophysical Education
John C. Hollister, Head of the Dept of Geophysics, Colorado School of Mines, Golden, Colo.

Address by S.E.G. President

How Geophysicists Can Meet the Present Situation
Dr. J. P. Woods, Director of the Geophysical Laboratory, Atlantic Refining Co., Dallas, Texas.

The primary purposes of this meeting, relative to the current situation in exploration geophysics (particularly in the oil industry) and its outlook for the future, are as follows:

1. To present authoritative information on various aspects of the situation.
2. To offer the opinions and analyses of recognized leaders in geophysics and related fields.
3. To provide a forum for discussion by those attending, particularly geophysicists and representatives of management.

The material to be discussed in the papers will be pertinent to all areas of exploration activity, but particularly to those in the United States and Canada.

The Canadian Society of Exploration Geophysicists will hold their Annual Meeting in conjunction with this conference.

Further details, regarding the hour at which each paper will be given, the speakers for the other topics and the possibility of a luncheon or dinner meeting, will be published as soon as they are available

ABSTRACTS

Beginning with the year 1957, the *Bulletin (Izvestiya) Academy of Sciences, USSR, Geophysics Series*, has been available in English translation under the auspices of the American Geophysical Union. A large number of articles which appear in this journal contains subject matter of direct or indirect interest to the members of the Society. It is not feasible to obtain reviews for publication in GEOPHYSICS of all such papers. Accordingly, beginning with the issue of February 1961, titles and abstracts, if available, of all papers on subject matter which may be of interest to members of the Society will from time to time be reprinted in GEOPHYSICS. Titles and abstracts will be selected to include principally those dealing with all branches of exploration geophysics and geochemistry and with those disciplines which are closely related. Principal omissions will be in meteorology, hydrology, and some branches of oceanography and aeronomy.

Bulletin (Izvestiya) January, 1960 Academy of Sciences, U.S.S.R., Geophysics Series.

Convection in the Earth's Mantle

E. N. LUSTIG

Less than 6% of the total output of the sources of heat responsible for convection can be transmitted to the earth's crust, that is not more than 10^{26} erg/year. This does not contradict an estimation of the output of tectonic processes according to seismic data.

The Frequency Theory of Interference Systems. I

F. M. HOLZMANN

The paper examines problems of the synthesis of interference systems for the separation of waves having different apparent velocities in the directions of the coordinate axes. In the general case, the synthesis of interference systems is reduced to the selection of three-dimensional frequency characteristics and to the calculation of their reciprocal Fourier integral. The frequency characteristics of the discrete systems are periodic. An examination is made of the basic concepts of the theory of filtration of velocities on the basis of which the frequency characteristics are selected. The article adduces examples of the synthesis of interference systems by the assumed values of the apparent velocities of effective and interference waves.

Dynamic Peculiarities of Multiple Reflected "Water" Waves in the Ocean and Their Use in the Determination of Elastic Waves in Sediments

S. M. ZVEREV

In this paper an analysis is conducted of the travel time and amplitude curves of multiple reflected water waves found on profiles of deep seismic sounding in the Sea of Okhotsk and the Pacific Ocean.

It is shown that the shape of the amplitude graphs is determined by a change in the reflection coefficient in relation to the incidence angle at the ocean floor.

Possibilities are discussed for determining the velocity in sediments by the experimental amplitude graphs of multiple reflected water waves.

Origin of the Reversed Magnetization of Volcanic Rocks from Armenia and the Kuril Islands

G. A. POSPELOVA

Investigation of volcanic rocks from Armenia and the Kuril Islands showed Early Quaternary—Upper Pliocene rocks to be magnetized in a direction opposite to the present geomagnetic field. A detailed investigation of the magnetic properties, the stability characteristics, the content of the ferromagnetic fraction, and of the thermo-remanence of directly as well as reversely magnetized samples in the laboratory did not reveal any great differences among them. The origination of the reversed polarity of the rocks can be explained quite justifiably with the reversal of the earth's magnetic field as a whole during Early Quaternary-Upper Pliocene times.

On Short-Period Variations of the Regional Electromagnetic Field

A. G. KALASHNIKOV AND E. N. MOKHOVA

Short-period variations of the earth's electromagnetic field (pulsations, pulsation trains and bays) registered simultaneously at four IGY stations in the USSR are discussed.

A Study of the Triboelectric Effect in Rocks and in Certain Dielectrics by Means of a Dynamic Method

E. I. PARKHOMENKO

It is found that marble, plexiglas, polystyrene, amber and ebonite, having been electrified by friction, display very strong electrical oscillations when elastic vibrations pass through them. Conclusions are made con-

cerning the bulk polarization of the dielectric appearing during the frictional electrification process based on the presence of polarity in the effect and on observations of the inverse tribolectric effect in marble and plexiglas.

Study of the Propagation of Elastic Waves of Ultrasonic Frequency Over Small Distances in Rocks, Under Conditions of Natural Deposition

V. I. Myachkin and R. N. Solov'eva

A method is presented for studying the propagation of elastic waves with frequencies on the order of 50 kc, at short distances. Results of studies in the Kalush potassium mine are described, where the velocities and elastic constants in the potassium salts are determined.

Certain Results of Model Investigations According to the Inductive Method

B. S. Svetov

Converted and Reflected Waves on Azimuthal Seismograms of Earthquakes in the Garm Region

E. V. Glivenko

Some Special Features in the Structure of the Earth's Crust in Central Asia According to Records of High-Power Explosions

V. I. Ulomov

On the Evaluation of the Intensity of Earthquakes in the Territory of China

E. F. Savarensky and Mei Shi-Yun

The Feasibility of Using the Earth's Natural Electromagnetic Field for Geological Surveying

N. P. Vladimirov

An Apparatus for Measuring Small Remanent Magnetization of Rocks

V. I. Dianov-Klokov

An apparatus for measuring small remanent magnetization of rocks is described; it utilizes the "rock generator" principle. For cubic samples with dimensions 24×24×24 mm and a time constant of $\tau \cong 1$ sec the sensitivity of the apparatus amounts to $I_{min} = 5 \times 10^{-8}$ gauss (signal to noise ratio = 1). The sample holding chuck which has a light mass introduces small systematic perturbations which can be circumvented without any special arrangement to compensate for them. The possibility of constructing a pulse type "rock generator" of higher sensitivity is also considered.

On the Diurnal Variation of Earth Current Disturbances as Observed by Soviet Stations During the IGY

V. M. Mishin and O. M. Barsukov

The Dependence of the Damping of Impulses in Layers of Finite Thickness on the Frequency Spectra

O. G. Shamina

The Influence of the Character of a Lava Flow on the Formation of Remanent Magnetization of Rocks

G. I. Kruglyakova and V. V. Kruglyakov

Seminar on Seismic Regional Divisions of the Carpathians

Chronicle

Geophysical Prospecting, Vol. 8, No. 3, Sept., 1960, Official Journal of the European Association of Exploration Geophysicists.

Experiments with Static-Resistant Blasting Caps

J. H. Banville and H. Richard

Premature detonation of seismic blasting-caps may be caused by the accumulation of an electrostatic charge. This is especially true in desert areas where there are many sandstorms.

Two makes of static resistant cap have been tested in the laboratory and the results compared with those for non-resistant caps made by the same manufacturers. The full results are given in the table, the breakdown voltage for the resistant caps is in the range 20–30,000 volts as compared with the range 10–15,000 volts for the ordinary cap.

It is strongly recommended the static resistant caps should always be used and that experiments on premature detonation from this cause should be made in the field.

In January 1960, 20 crews in the Sahara used a total of 146,150 static-resistant blasting caps.

Diffraction Problems in Fault Interpretation

Bruno F. J. Kunz

Distinguishing between diffractions and true reflections is often difficult and may lead to misinterpretations. In the Molasse zone of Upper Austria, numerous faults were established by seismic surveying. Diffractions were observed at several antithetic faults but not at synthetic faults. As an example, a seismic record section of the Steindlberg structure is shown. The reflections from the base of Tertiary and from the Creta-

ceous-Jurassic contact run parallel over long distances, and so do the less important reflections lying above and between. If, contrary to the general trend, the reflection from the base of the Tertiary approaches the underlying reflection from the Cretaceous-Jurassic contact, or if the latter diverges from the former, this is considered a criterion for a diffraction.

Development of New Techniques Applied to the Search for Stratigraphic Traps

L. Carissimo and O. D'Agostino

The "Summarizer" is a new device designed and manufactured by the Agip Mineraria Electronic Laboratories which gives an output which is a function of the total energy detected by the geophone spread. This paper gives some examples of its use in stratigraphic mapping.

Test surveys have been carried out in an area of the Po basin where the formations show many facies variations. Three gas fields of known geological features were considered. The usefulness of various methods of representation was evaluated as well as the contribution given by the new device. It was noticed that the results given by the "Summarizer," when added to those obtained by standard and "variable area" sections, supply the interpreter with new useful elements. Lateral facies variations between gravels and shales have been recognized and localized.

The Use of Amplitudes in Refraction Shooting—A Case History

P. N. S. O'Brien

On a group of seismic refraction records there occurs a late arrival with the same apparent velocity as an earlier arrival. It was first thought that the late arrival travelled along the same refractor as the earlier one but had been delayed in the overburden either by multiple reflection or by P-S (dilatation to shear) conversion. Either of these two mechanisms could be made to fit the time-distance data. A study of the ratio of the amplitudes of the two events showed that the observed ratio was about ten times that to be expected on either of these hypotheses. Also, the rate of attenuation of the earlier arrival (3.7 ± 1.0 db/1000 ft) was appropriate to a thin layer while the rate for the later arrival (0.74 ± 0.30 db/1000 ft) was appropriate to a thick layer. Accordingly, the later arrival was identified as a refraction from a deeper layer.

The subsequent depth section agreed very well with that found by drilling.

Elastische Wellen im Anisotropen Medium Nach Eine Makroseismischen Untertage-Messung

S. J. Duda

In some mines of the Siegerland, besides dilatational and shear waves, an additional direct wave has sometimes been found the velocity of which was somewhat lower than that of the shear wave. Investigations were carried out with the object to establish the directions of oscillations and the velocities of all three kinds of waves. It was the purpose to draw conclusions as to the character and the causes of the appearance of the third wave.

By these investigations the wave having the lowest velocity can be identified as a second shear wave. This points to the fact that double refraction of the shear wave is taking place, the wave of higher velocity being a pure transverse wave and the wave of lower velocity being a quasi-transverse wave.

As a result of these measurements the examined medium is shown to have a transverse isotropy due to stratification. It is, however, not possible to decide whether there exists also an anisotropy due to schistosity.

Some further calculations show that the wave of lowest velocity can not be explained as a surface wave propagated on the walls of the gallery.

General Method for Construction of Trajectories and Wave-Fronts Diagram for Any Velocity Distribution

V. A. Olhovich

A graphical method is presented for construction of trajectories and wave-front diagrams for any velocity distribution.

The analytical solution is given for the case when the time-depth curve shows a flexure, that is, when the velocity increases down to a certain depth and, after reaching a maximum, begins to decrease.

A numerical example is considered for the computation of a trajectory.

A Generalized Cagniard Graph for the Interpretation of Geoelectrical Sounding Data

O. Koefoed

The Cagniard method of interpreting geoelectrical sounding data is based on the use of an empirical graph which expresses the relation between the resistivity and thickness of the second subsurface layer on one side, and on the other side the replacement resistivity and replacement thickness which are derived from the two-layer sounding curve which is asymptotic to the second branch of the observed sounding curve. In his method separate graphs of this type are required for different values of the resistivity of the third subsurface layer. In the present paper a generalized Cagniard graph is derived which has the advantage of being independent of the value of the resistivity of the third subsurface layer. Finally, the accuracy of the method is discussed, and a procedure is described for extending its use to cases where more than three subsurface layers intervene.

PERSONAL ITEMS

DR. GEORGE V. KELLER, former geophysicist with the U. S. Geological Survey, was named assistant professor of geophysics and physics. His bachelors, masters and doctors degrees all came from Pennsylvania State University.

C. H. G. OLDHAM formerly Senior Research Geophysicist with California Research Corporation has accepted a Fellowship which will enable him to study aspects of the Earth Sciences in the Orient. He is presently studying languages at the School of Oriental and African studies in the University of London.

MR. WALTER RUSKA resigned as president of Ruska Instrument Corporation to establish offices as a consultant in various phases of instrumentation. His new address is 4215 Richmond Ave., Houston 27, Texas.

DR. HUGHES ZENOR is now Professor of Geophysics, Dept. of Geology, Missouri School of Mines, Rolla, Missouri.

MR. JAMES L. MOODY formerly with P. R. Rutherford, an independent oil operator, is now chief geologist for Rycade Oil Corporation.

J. BURLIN JOHNSON, formerly with Newmont Exploration Ltd., is now project leader in charge of rock fragmentation research with the U. S. Bureau of Mines, Minneapolis, Minnesota.

The University of Utah has announced the appointment of ANTHONY DEL PRETE, JR. of Amityville, N. Y. as the Pan American Petroleum Foundation fellow in geophysics at the University for the 1960–61 academic year.

Mr. Del Prete, who will study for the M.S. degree in geophysics, is a graduate of Amityville high school, attended Hofstra College, Hempstead, N. Y., and holds a B.S. degree in geology from the Missouri School of Mines at Rolla.

Dr. Leo J. Peters, formerly a Vice-President and Associate Director of Gulf Research & Development Company (Harmarville, Pa.), Gulf Oil's research subsidiary, has been promoted to the newly created office of Vice-President and General Administrator of GR & DC. In his new position, Dr. Peters will be responsible for the day-to-day operations of the Laboratory.

A pioneer in the field of geophysics, Dr. Peters is recognized both nationally and internationally as a geophysicist and communications engineer. He was the author of the first book in America on vacuum tube circuit theory.

Educated at the University of Wisconsin, he was graduated with his B.S. degree in Electrical Engineering in 1919, and earned his Ph.D. degree in 1929. During this period he served for a time as Assistant Professor of Electrical Engineering at the University of Wisconsin.

As a member of the staff of Gulf Research & Development Company, with which he has been associated since 1929, Dr. Peters has devoted his time to many phases of the fundamental theory of geophysical methods, the interpretation of grophysical data, and the design of equipment.

Dr. Peters was named Director, Geophysical Operations, GR&DC in 1945 and in 1951 he was assigned additional responsibility as an Assistant Director of Research, a position he held until his appointment as Associate Director of Research and his election as a Vice-President, GR&DC, in 1953.

He is a Fellow of the American Physical Society, Senior Member Institute of Radio Engineers, Member of American Institute of Electrical Engineers, and Active Member, Society of Exploration Geophysicists and the Pittsburgh Geological Society, and American Society for the Advancement of Science.

W. E. DICKSON Supervisor for G.S.I. (Bahamas) Ltd. has moved from London to Madrid, Spain. Present office address is: Castellana Hilton Hotel, Room 319, Madrid, Spain.

R. H. PARKER, Executive Vice-President of Dresser Electronics, SIE Division, has announced that ROY F. BENNETT has joined the firm as Assistant to President GEORGE A. PECK. This is a new position established to foster cooperative research and development work by industrial and governmental agencies in earth-science fields.

MR. BENNETT, most recently a petroleum exploration consultant in Oklahoma City, was Chief Geophysicist and Foreign Exploration Manager for Sohio Petroleum Co. for fifteen years. Prior to these duties he had been with geophysical contracting companies for thirteen years.

He is a member of the American Association of Petroleum Geologists and Society of Exploration Geophysicists and has been active in both organizations. He is a past-president of SEG.

Mr. Bennett will reside in Houston, Texas.

DR. JOHN S. STEINHART is now a National Science Foundation Fellow at Department of Terrestrial Magnetism, Carnegie Institution of Washington.

DAVID M. MUIR, formerly with Empire Geophysical Co.'s Velocity Logging Division, has been promoted to District Manager of the Mississippi District for Pan Geo Atlas Corporation. Pan Geo Atlas Corporation purchased the Velocity Logging Division of Empire Geophysical Company in Feb. of this year.

MR. MARTIN J. GOULD terminated employment with Space Technology Laboratories, Inc., and commenced employment with the Aerospace Corporation.

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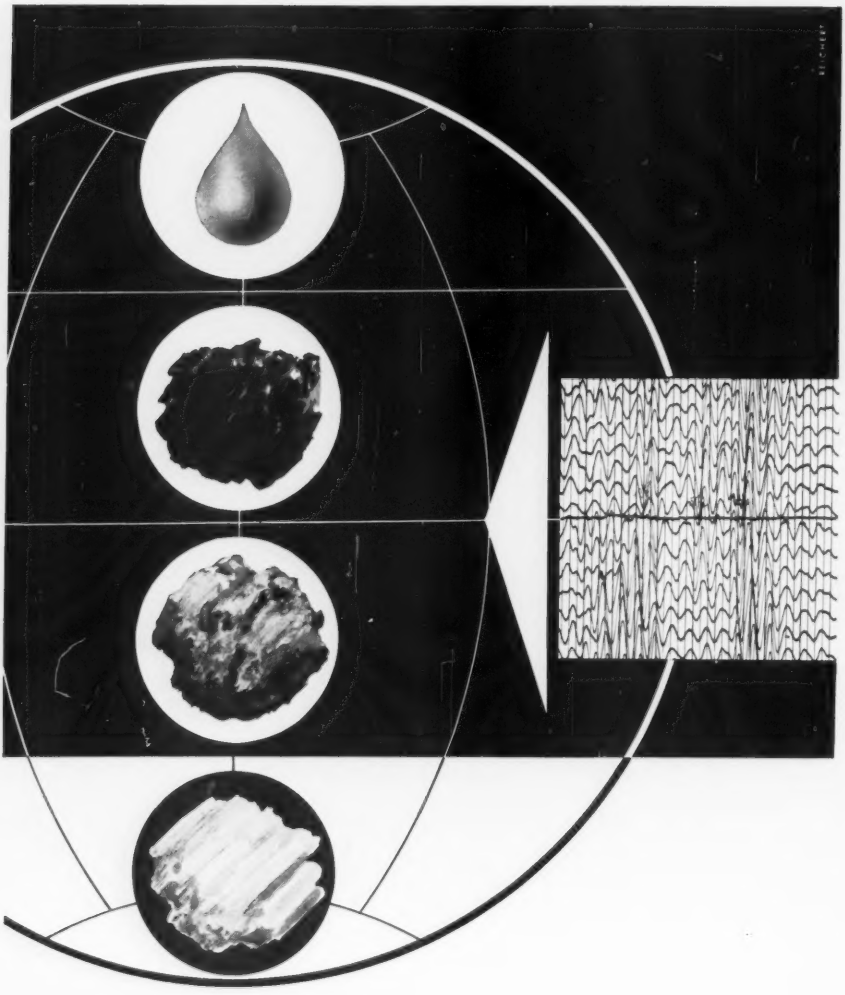

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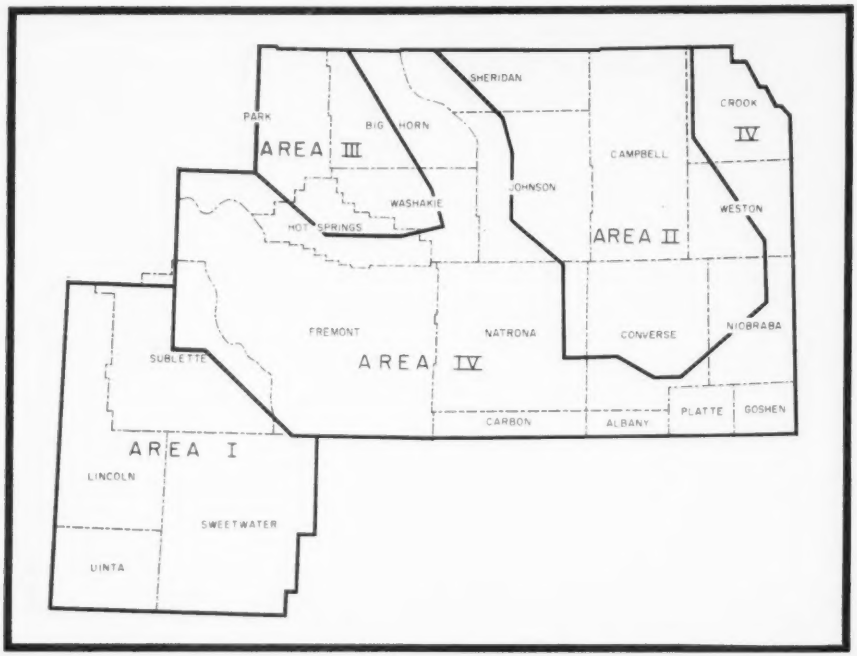

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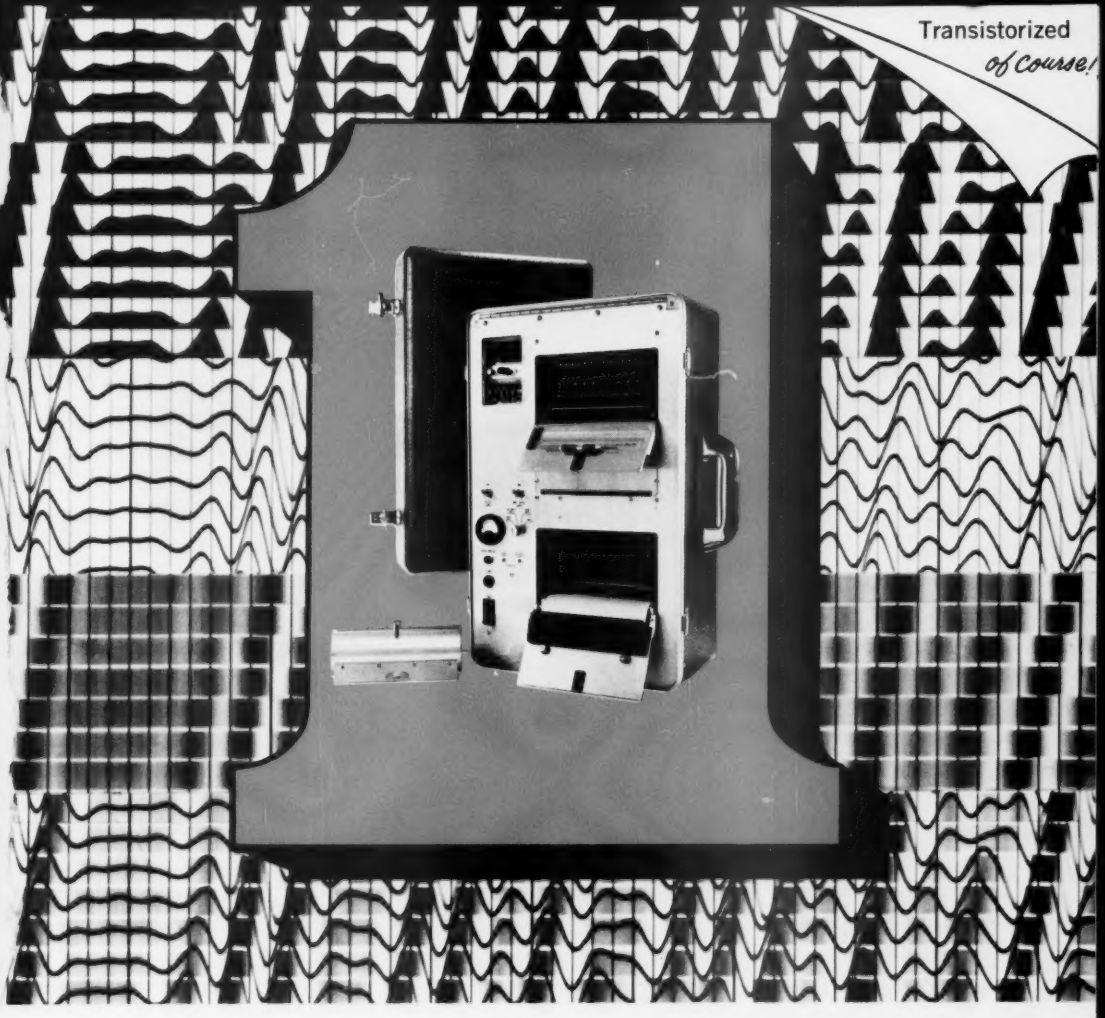

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Signal-to-noise ratio:	60 db (rms), 1 to 500 cps with noise cancelling. 54 db (rms) 20 to 200 cps without noise cancelling. (Peak-to-peak noise averages 6-10 db higher than rms noise)
Harmonic distortion:	Less than 1%
Crossfeed:	Below noise level of recording system
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Dimensions:	MR-20 Recorder—8¼"W x 24½"H x 15"D MU-20 Master Unit—8¼"W x 24½"H x 10½"D
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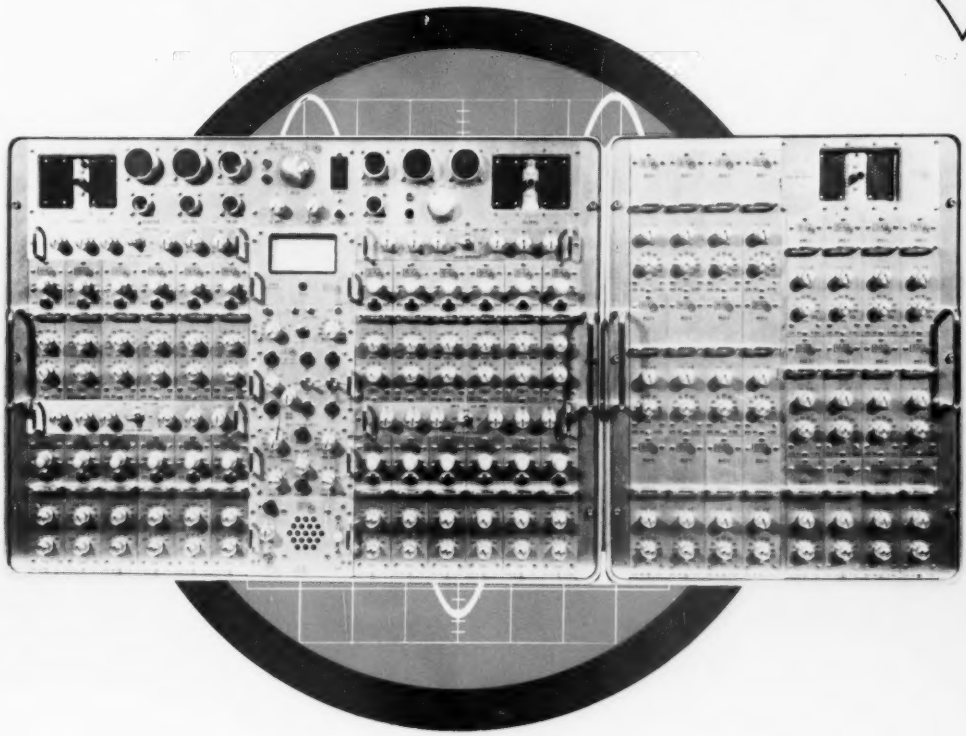

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The broad band response extends from 3 to 500 cps. Ten logarithmically-spaced cut-off frequencies are provided — from 16 to 135 cps for the low-cut and 23 to 235 cps for the high-cut filter positions. One or two sections (18 or 36 db/octave) may be used.

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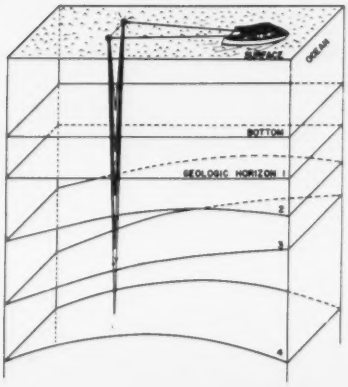

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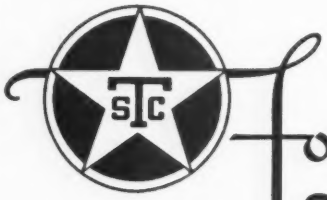

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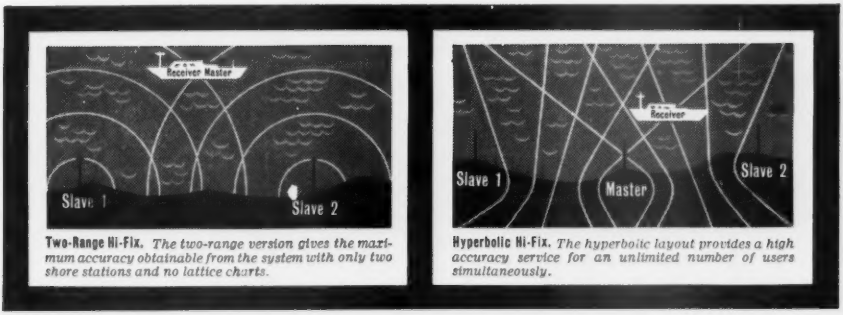

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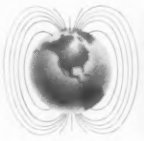

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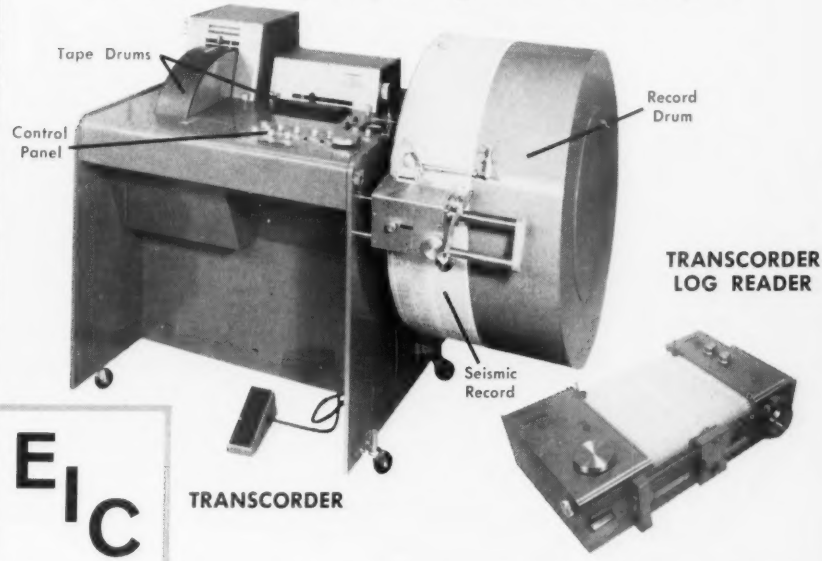

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The Transcorder, EIC's new data-transcribing device, transcribes seismic data onto any standard geophysical tape from paper records, from other sizes of magnetic tape, or, using the Transcorder Log Reader, from well logs. A reproduction of a seismic trace being transcribed can be produced simultaneously for checking purposes.

Magnetic tapes produced by the Transcorder can be processed by playback systems that permit mixing, selective filtering, correcting for moveout, weathering, and elevation, and plotting cross sections by the conventional trace, variable-area, or variable-density methods.

The paper record being transcribed onto tape is mounted on a large revolving drum. The magnetic tape is mounted on another drum that is servo-driven at an infinitely variable rate. The Transcorder will accurately transcribe paper records recorded at speeds ranging from 7.5 to 15 ips. The magnetic recordings produced are accurate within $\pm 1\frac{1}{2}$ ms of the original record at all times.

The Transcorder operator guides the tracking head as the record-carrying drum revolves. (Unskilled office personnel can operate the Transcorder.) The traces are individually transcribed to magnetic tape.

The Transcorder Log Reader, an accessory, permits transcribing well logging data onto magnetic tape in the same manner as conventional seismograms. The resulting tapes can be then converted to cross sections by seismic data reduction systems.

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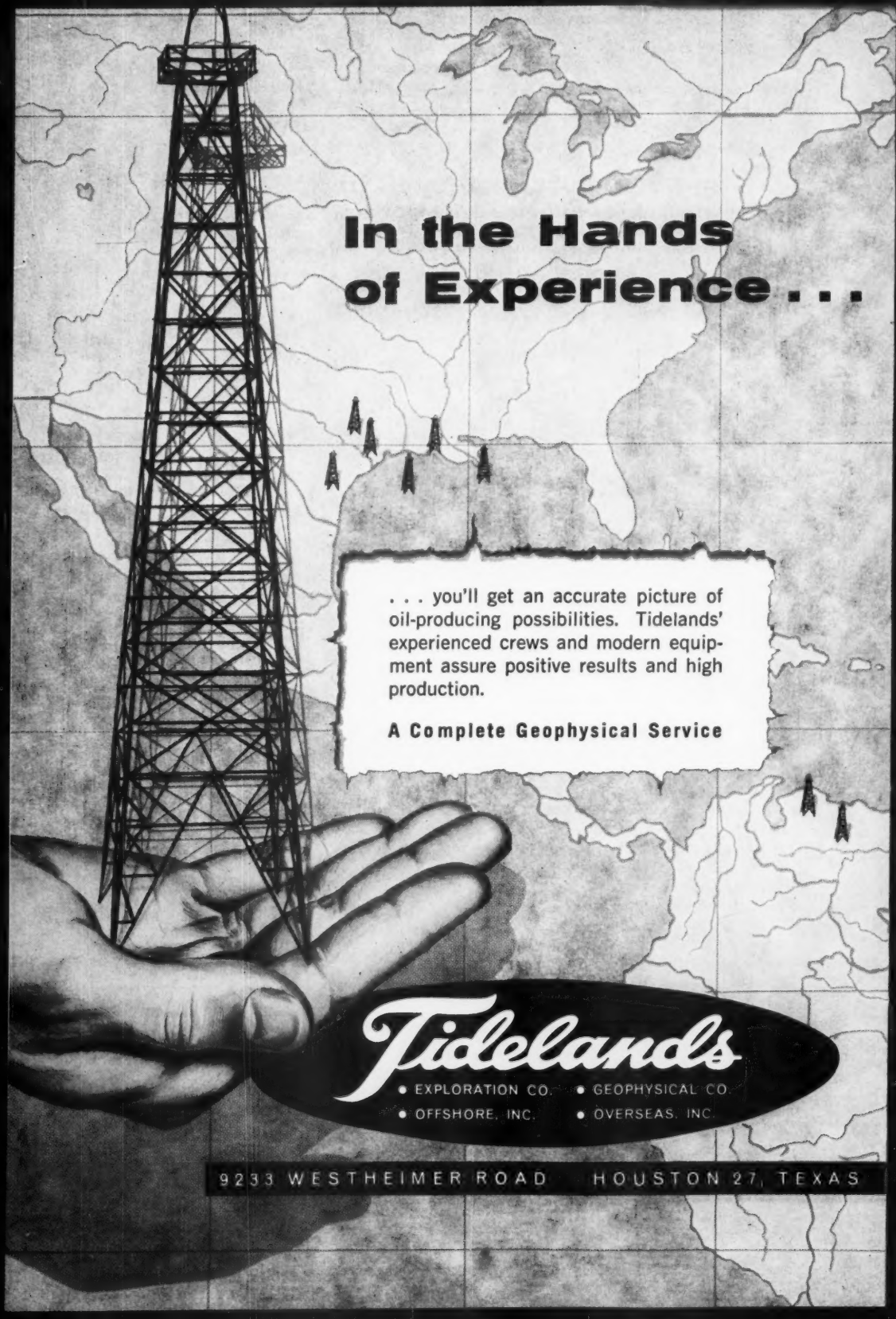
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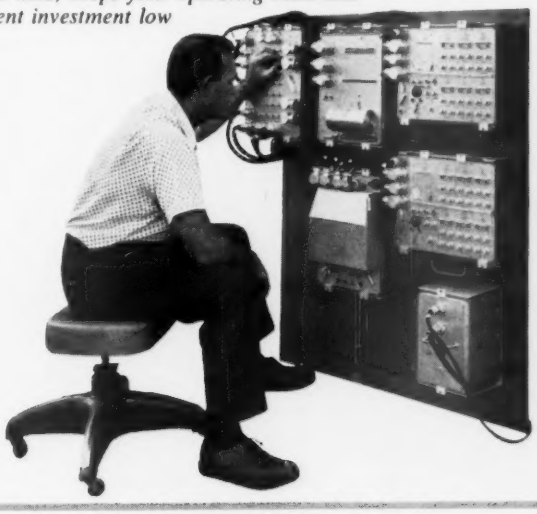

EIC

Although it weighs only 157 lb, the PSS-50 is a complete seismic system, consisting of two 12-channel seismic amplifiers, a tape-transport unit, a translator unit, and a master control unit.

The system's low cost and weight were gained by designing it to utilize fully the capabilities of magnetic tape and by including only needed filtering and display capabilities. The result is a truly portable system that performs superbly.

The seismic amplifiers have a flat frequency response from 8 to 250 cps. Filtering is provided by a separate plug-in unit. Filtering available includes 12 to 24 db per octave slopes, with 20, 30, and 40 cps cutoff points. Cutoff frequencies can easily be changed by plug-in capacitance boards.

A master control unit provides uphole level control, leakage and continuity testing, trip indicator and manual control, trip sensitivity control, master suppression control, avc on-off control, and a test oscillator. Timing accuracy is ± 1 ms.

The tape transport unit has a full 28-channel magnetic recorder, featuring standard EIC door - mounted recording heads. Heads can be interchanged without disassembling the tape transport. Recording heads have excellent low-frequency and transient response. The accurate, reliable drive system uses a hysteresis synchronous motor and a spur-gear transmission.

The translator unit has a playback amplifier with additional avc and filtering control. Traces are displayed on electrosensitive paper by a rectilinear pen writer. Each data channel is played out sequentially and automatically. Timing is provided by preprinted timing lines, with the 100 cps timing trace from the tape played out as a check. Two paper speeds are available, one for a full-length record, the other for expanding the first third of the record (covering the first-break region) over the full paper length. Accuracy from trace to trace is ± 1 ms.

Power required for the PSS-50 is 12 v at 8 a during standby and 18 a while recording.

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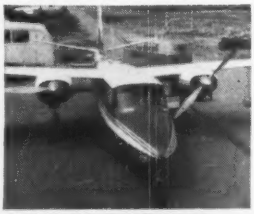

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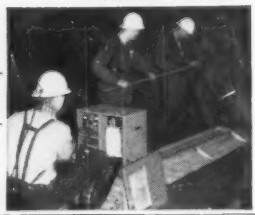

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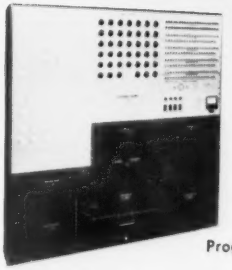
Field Tape Playback Unit

Plotting and Re-record Assembly



Programming Assembly

C-850

EIC

When you own the C-850, you have the most flexible single system available for sequential playback of magnetic tapes. It lets you make maximum static corrections of ±100 ms and dynamic corrections up to 400 ms (at a maximum rate of 500 ms per sec). Timing accuracy is ±1 ms. Any geophone spread length or arrangement can be handled.

During playback, time-corrected seismic data are plotted simultaneously to photographic cross sections. You can choose conventional - trace, variable - area, or variable - density cross sections, or any two of these three. Seismic data can be referenced to any desired datum plane on the cross-section plots. As many as 864 traces can be recorded on a single cross section, which may be as large as 72 x 72 in.

Corrected data are re-recorded during playback for future evaluation. As many as 12 channels of re-recorded tape can be played back for mixing, compositing, or stacking to cross-section plots.

The C-850 can be supplied with any standard-size tape transport. It handles up to 50 seismic and information channels at tape speeds of 7.5, 3.75, or 3.6 ips. It can reproduce direct, FM, or PWM recordings. Re-recording is by FM. Cross-section plotting speed is from 7.5 to 10 ips.

Distortion on FM is less than 1%, on direct magnetic recording, less than 2.5%. Frequency response is from 5 to 500 cps. Signal-to-noise ratio is 52 db (rms-rms) on direct recording, 46 db (rms-rms) on FM.

Such standard EIC design features as door-mounted recording heads and 400-cps hysteresis synchronous motors make the C-850 reliable, easy to maintain, and relatively inexpensive.

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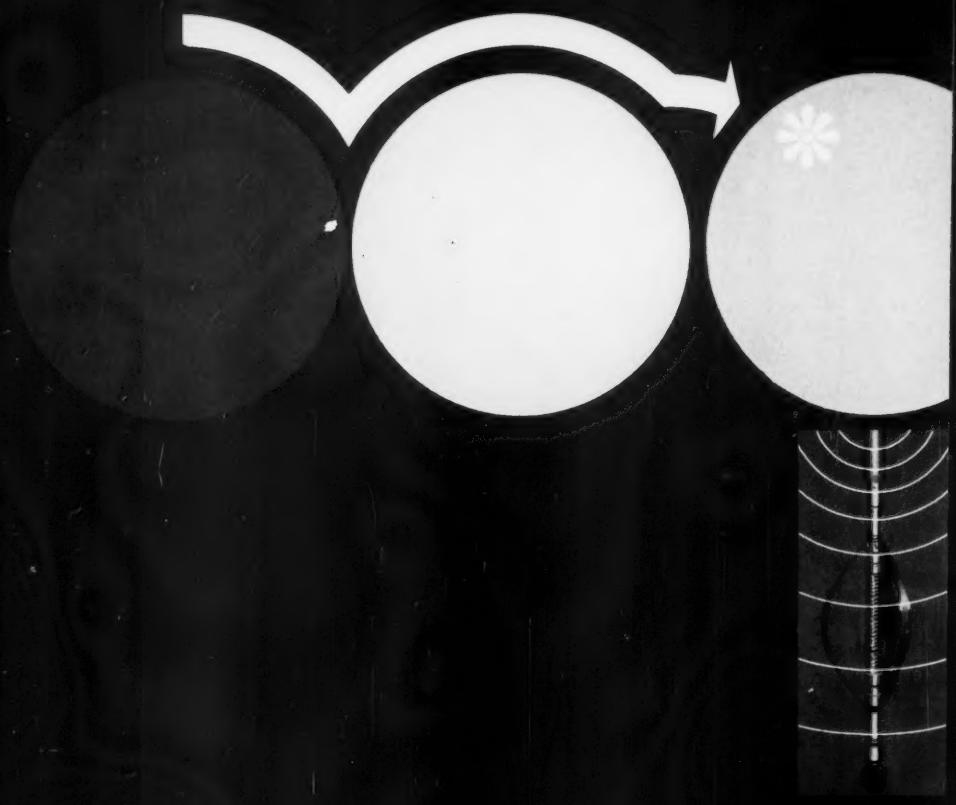

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PB 50/60

Keyboard Input Unit

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The PB-50/60 sequential playback system was engineered and built to give reliable service under adverse field conditions. Its single-console construction makes it easy to move from one location to another, and its rugged, simple construction makes it easy to maintain. Despite its low cost, the PB-50/60 gives you great flexibility of operation and ±1 ms accuracy.

Normal moveout corrections up to 240 ms are available at a maximum rate of 500 ms per sec. Maximum weathering and elevations corrections of ±100 ms can be applied. All corrections are inserted easily and rapidly by a keyboard input unit.

Timing lines on cross sections are recorded directly from field timing signals, giving you accurate trace plots that are in true relation to each other and to record time. Seismic information can be accurately referenced to any desired datum plane. Either conventional-trace or variable - density cross sections are plotted photographically on 24 x 72-in. tape or film. This system can be supplied with any standard-size tape transport.

Modifications of the basic PB-50/60 can be supplied to meet specific requirements.

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this direct recording magnetic tape system updates seismic systems to provide high-quality tape-recorded data for analysis in seismic data reduction systems

DR-50

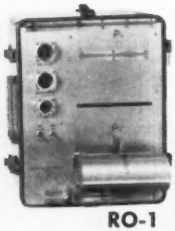
The DR-50 magnetic recording systems produced by EIC record up to 50 seismic and information channels. Record - reproduce heads have excellent low-frequency and transient response. They are mounted on the access door so that they can be inspected, adjusted, or replaced without disturbing the tape transport.

The neatly packaged plug-in amplifiers used as dual-purpose record and reproduce units provide proper playback compensation down to 5 cps.

The DR-50 features timing accuracy of ± 1 ms, with trace - to - trace accuracy of ± 0.5 ms. Frequency response is from 10 to 500 cps. Signal-to-noise ratio is 52 db (rms). Total harmonic distortion is 2.5%. The DR-50 is driven by EIC's reliable 400-cycle synchronous motor.

The DR-50 is available either with or without a buffer unit. The buffer is used when the seismic amplifier cannot drive the recording heads directly or when a superior signal-to-noise ratio is needed for field playback. EIC engineers are experienced at integrating systems with existing amplifiers and can provide turnkey installation of DR-50 systems.

you get dependable field performance from this rugged recording oscillograph



RO-1

The RO-1 recording oscillograph photographically records up to 28 seismic data traces on 6-in. paper or film. A 400 cps hysteresis synchronous motor provides uniform paper speeds from 3 to 45 ips. Speeds are selected by interchanging easily replaceable drive gears. Precise time correlation is insured by sharply defined timing lines. The RO-1 has 28 pencil-type galvanometers that are available in natural frequencies from 125 to 500 cps. Both galvanometers and front-surfaced mirrors can be adjusted readily in the field. Because the RO-1 produces very little noise in the battery circuit, a single battery can power both the camera and the seismic amplifier. This simplifies battery-charging problems and makes the RO-1 especially suitable for truck mounting.

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cut uphole shooting time and costs with this precision interval timer

you can obtain weathering and subweathering velocities accurately and efficiently with this interval timer, without using costly seismic recording systems

GT-1

EIC

EIC's GT-1 geophysical interval timer is a precision digital readout instrument that simplifies uphole shooting operations. It provides an immediate visual display of the time interval from shot detonation to the initial seismic wave received by an uphole geophone. Accuracy is ±0.5 ms. A maximum time interval of 255.75 ms can be recorded.

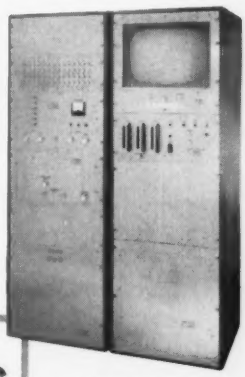
The GT-1 is completely transistorized. It is powered by self-contained dry-cell batteries. The unit's total weight, including batteries, is only 17 lb. Its aluminum carrying case is 16 x 9 x 7¾ in.

now you see results of filtering, stacking, mixing without waiting for cross sections

The MSS-100, a remarkable new multitrace electrostatic storage system developed by EIC, lets you store up to 28 seismic data traces for visual readout on a 17-inch, TV-type, video monitor. This advance in the art of handling seismic data can help you cut the cost of analyzing geophysical data.

The MSS-100 stores data from tape-recorded seismic traces in a special storage tube and displays them continuously on the monitoring tube. Traces can be displayed for as long as 20 minutes without appreciable deterioration. They can be erased instantly to permit storing new data.

Vertical timing lines can be displayed on the video monitor at 1/100-second intervals, with 1/10-second lines accentuated. Either the 1/100- or 1/10-second lines can be omitted if desired.



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MSS-100

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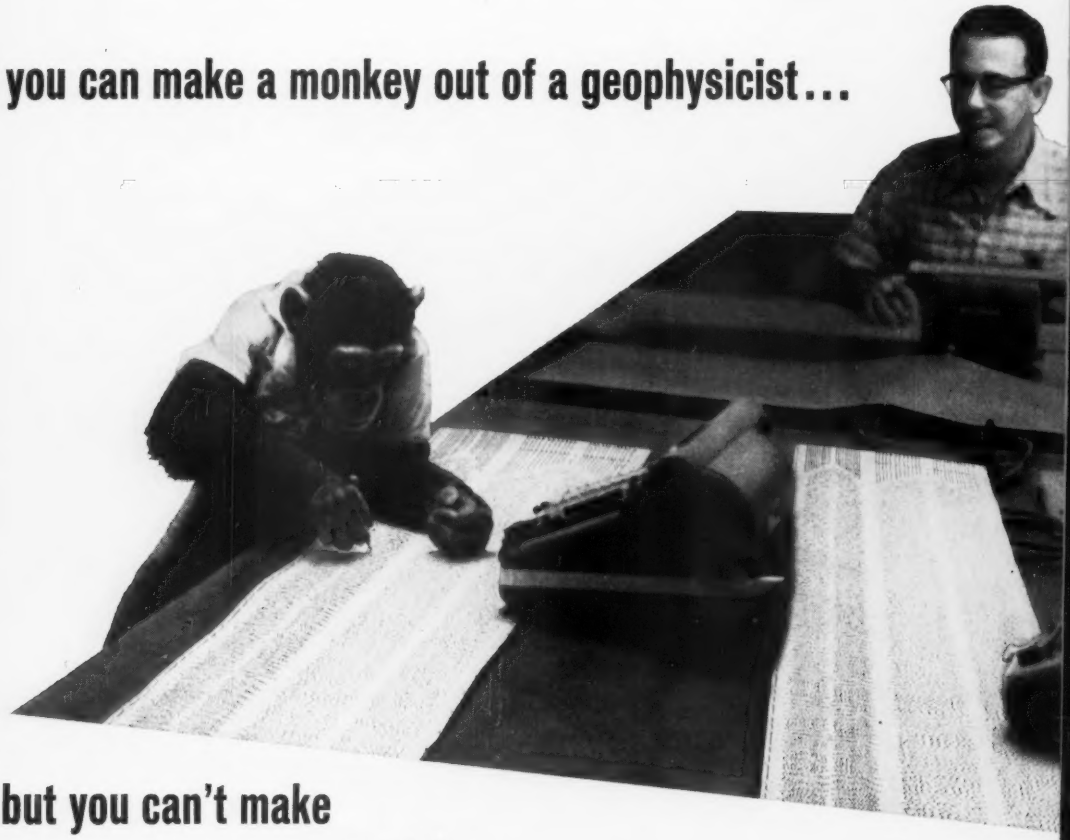
you can make a monkey out of a geophysicist...



but you can't make a geophysicist out of a monkey!

It doesn't take a monkey to tell you that you get only what you pay for — in the geophysics field as in others.

One of our camp followers, Fidel by name, puts on a pretty good act among the record sections, slide rules, and delicate electronic equipment and looks sort of professional behind a desk.

Fidel might be taught to perform some fundamental chores with only an occasional banana break, but if any oilfields were discovered through his antics, they would be strictly accidental — and you can't afford to gamble on accidents.

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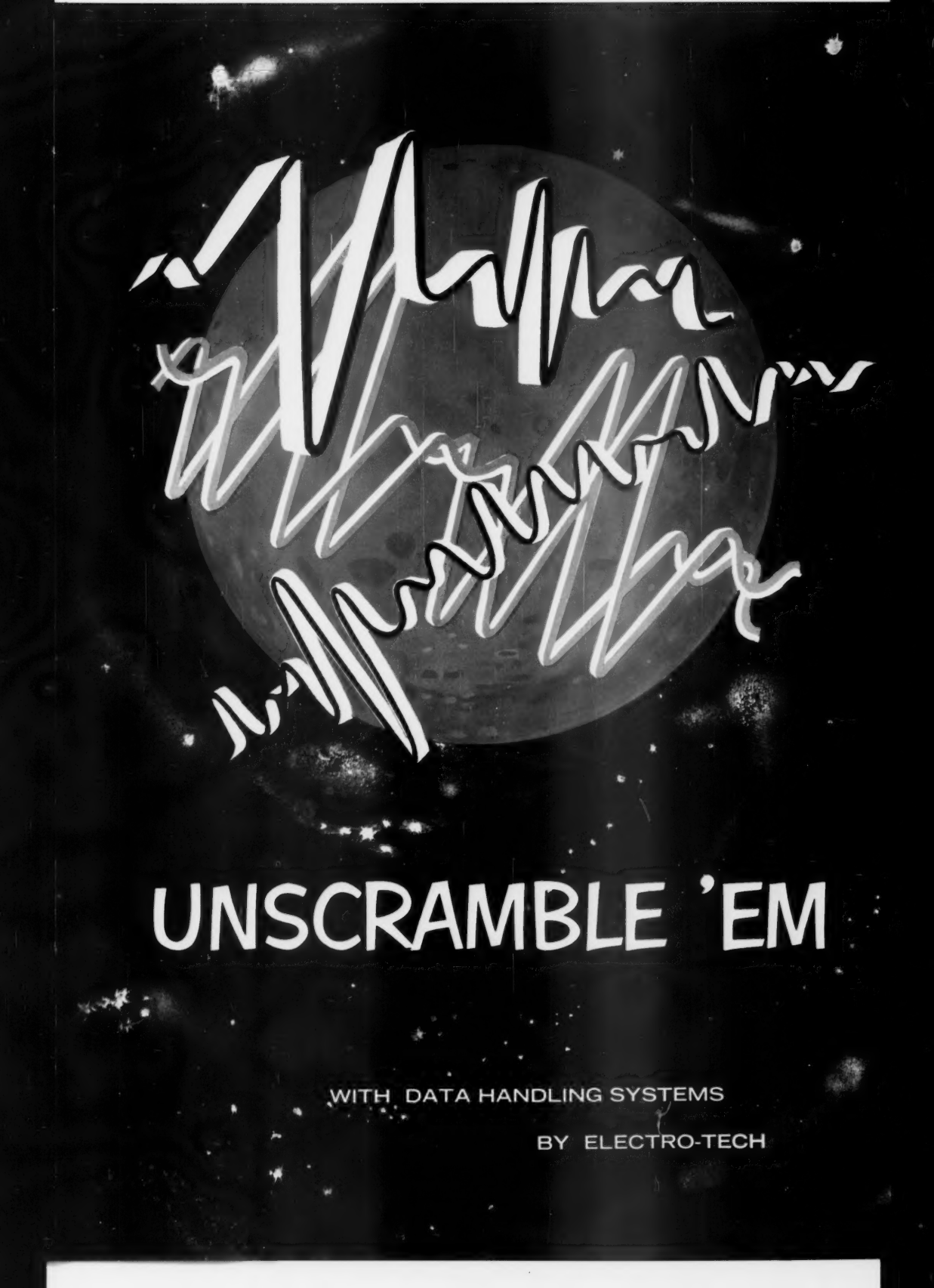
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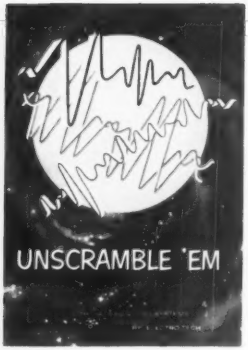

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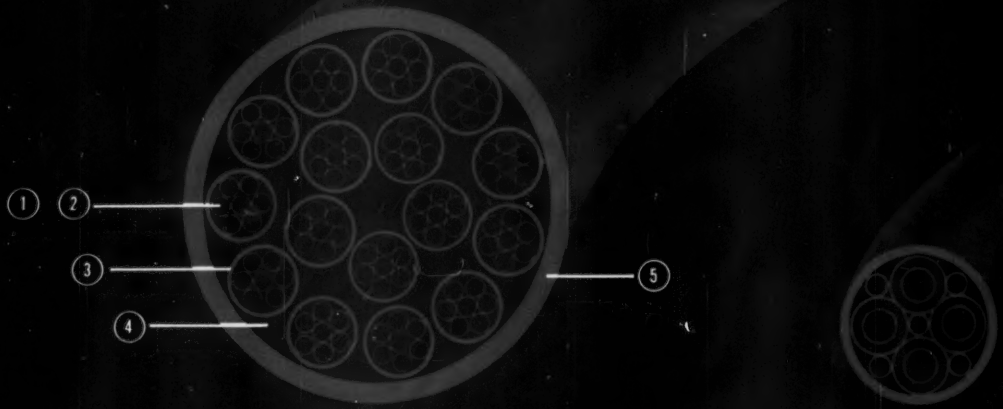

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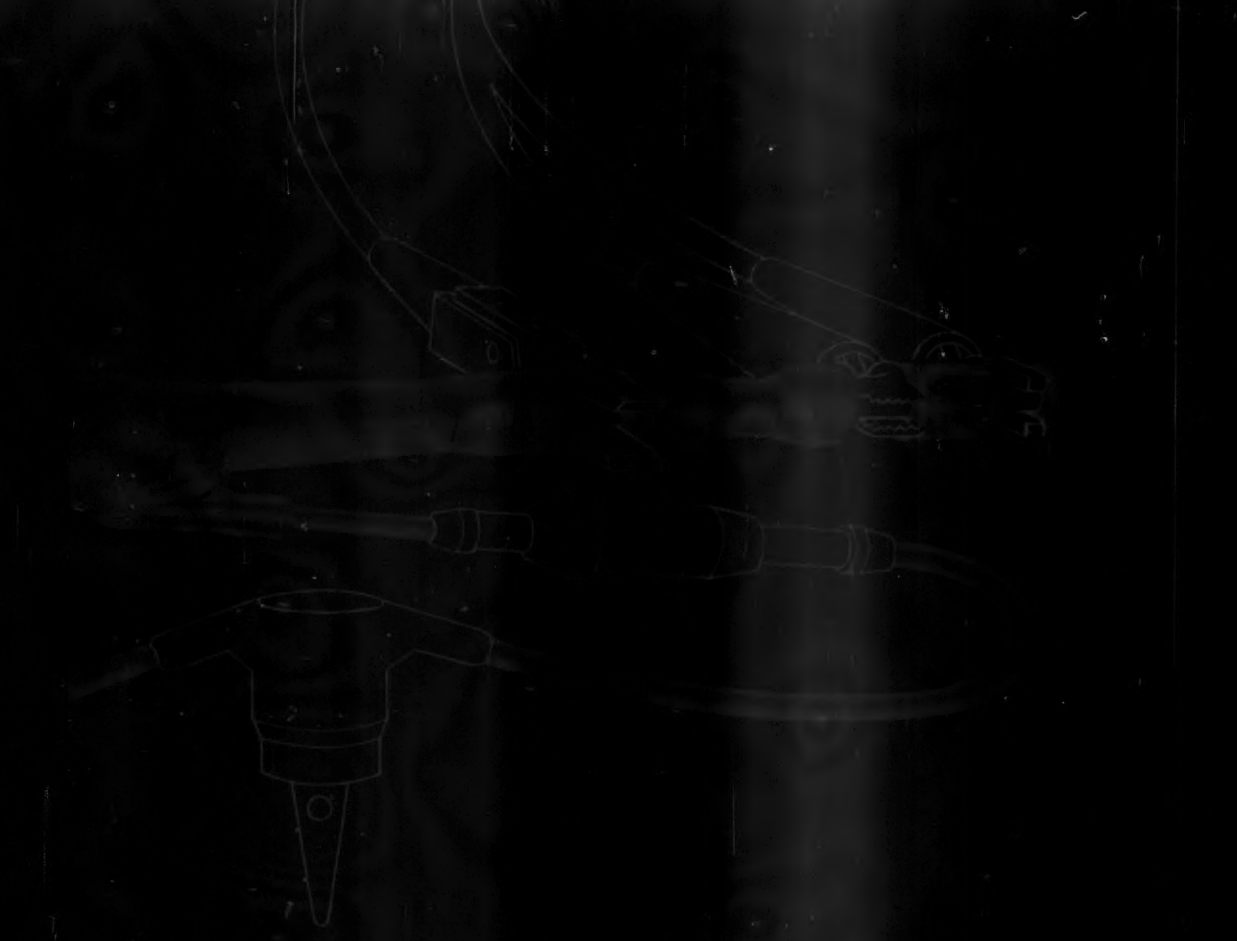

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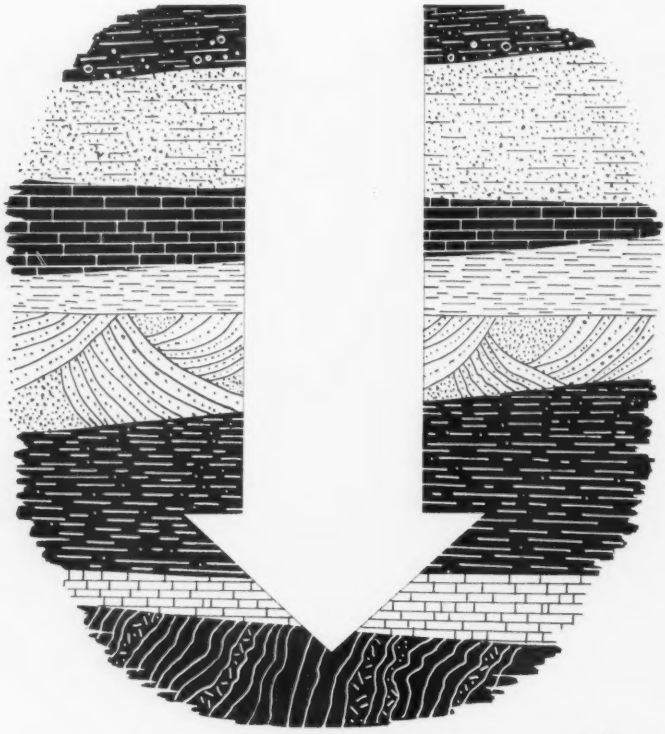

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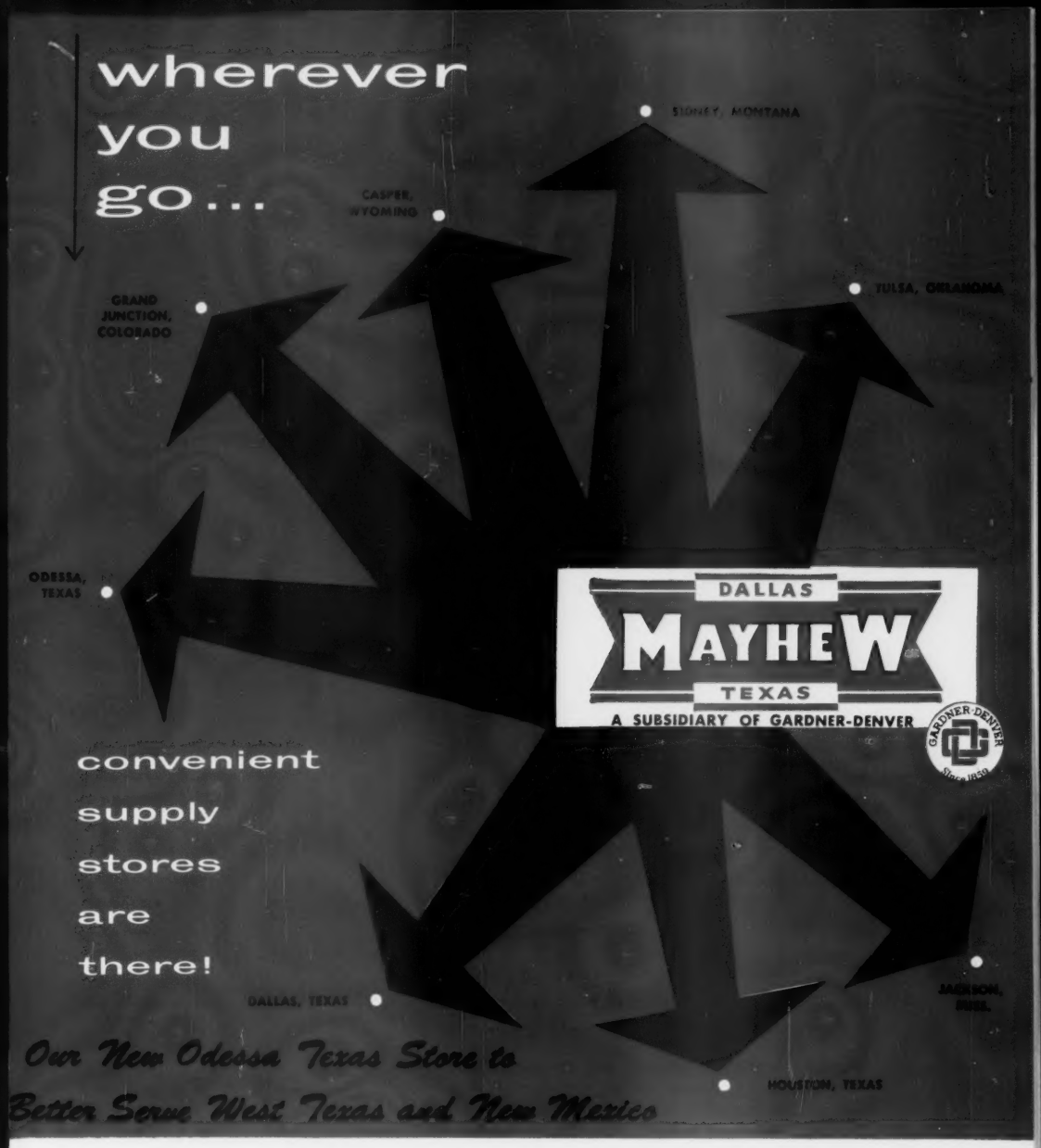

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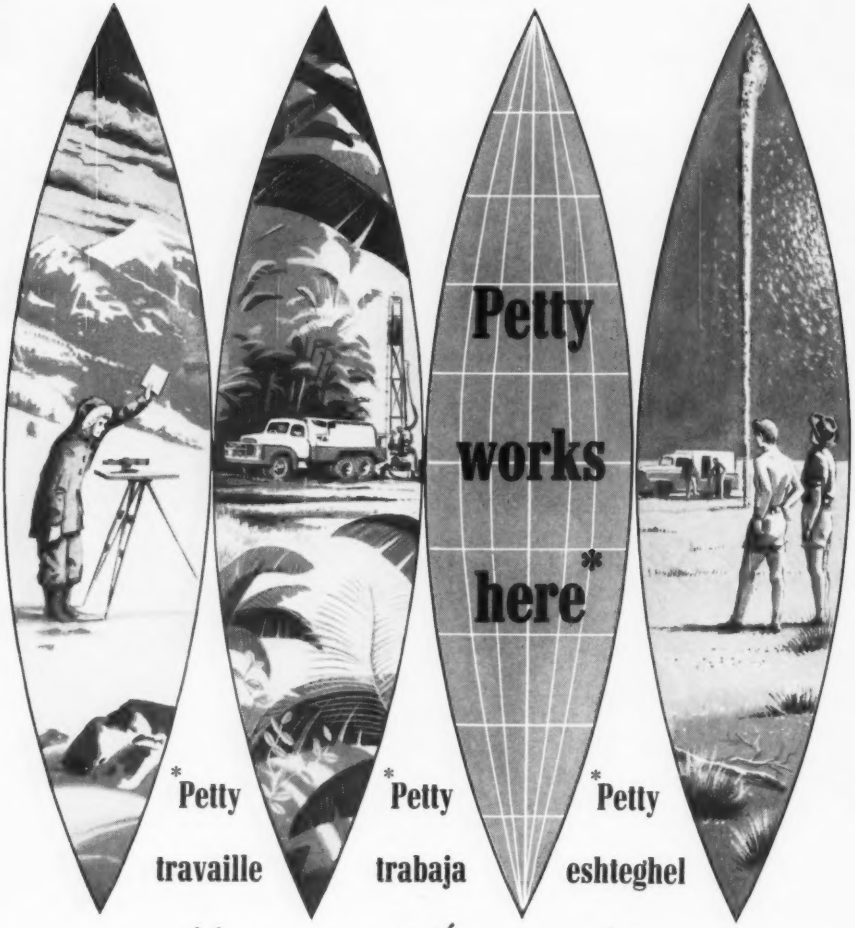

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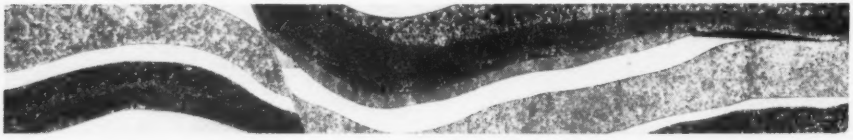

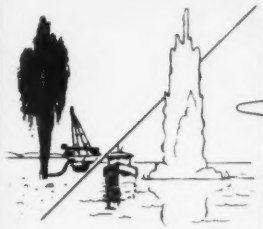

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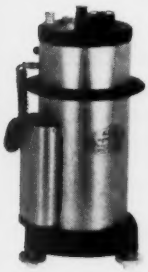

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Small Dial Constant—Specify constant desired*	Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available)	Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available)	Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available)	0.10-1.00 mgl./ Dial Division
Small Dial Calibration Linearity over full range	1 part in 1000	1 part in 1000	1 part in 1000	1 part in 1000
Small Dial Reading Accuracy	0.1 of Small Dial Division	0.1 of Small Dial Division	0.1 of Small Dial Division	0.1 of Small Dial Division
External Temperature Control	Temp. Stabilizer requires 1.00 watts power for a 100° F. differential. Four Rechargeable "D" Size Batteries maintain 90° F. differential for 10 hours and are mounted in removable pack on side of meter. Any 4.5 to 12 volt DC source may be substituted.	None	None	None
Small Dial Mechanism	Self counting, read from top and directly coupled (no gears for backlash) with screw which contacts quartz measuring spring.		Side and top reading, directly coupled (no gears for backlash) with screw which contacts quartz measuring spring.	
Large Dial Range — Specify range desired*	800 Dial Divisions x Large Dial Constant			Geodetics not available
Large Dial Constant	Standard 6.5 to 12.0 mgls./D.D.			Geodetics not available
Large Dial Calibration over full range (8 turns)	Curve furnished with values accurate to one part in 1000—measured over full range (8 turns).			Geodetics not available
Size, Inches: Diameter Height	7" 14"	7" 14"	5½" 10½"	5½" 10½"
Weight, Pounds: Net Including carrying case	9¾ lbs. 18 lbs.	7½ lbs. 15¾ lbs.	5⅛ lbs. 12 lbs.	5⅛ lbs. 12 lbs.
*Price of meter is determined mostly by the Ranges and Dial Constant Specified.				

Write for Bulletin No. GM-206

WORDEN Gravity Meters Are Made Exclusively By

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(Continued from page 10)

ging tool will replace truck-mounted equipment ordinarily required for the logging process.

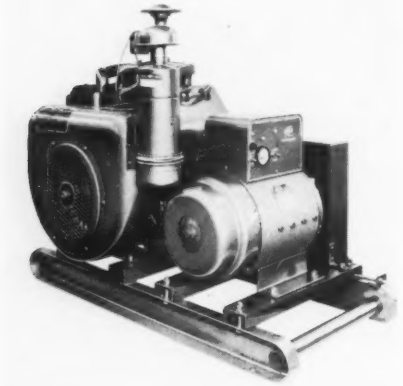
Completely transistorized, it carries its own batteries and is independent of outside power sources.

The new unit is capable of operating to a depth of 15,000 feet and will withstand temperatures in excess of 300 degrees.

Further information on the **Electro-Technical Labs** logging device is available by writing to the company, at **5134 Glenmont, Houston, Texas.**

ENGINE GENERATORS

New BALANCED Power Winco Engine Generators have just been announced by Wincharger Corporation, subsidiary of Zenith Radio Corporation, Sioux City 2, Iowa. Powered by a Wisconsin VH4D air-cooled gasoline engine, these new Wincos are rated at 12,000 watts A.C., and are equipped for remote starting. They are capable of producing ample power and energy for a wide variety of standby and portable power needs for industry, institutions, homes, farms and ranches, and for mobile power.



According to Mr. Lyman Phillips, Sales Manager, "these new BALANCED Power Winco engine generators permit the engine to operate at an OPTIMUM SPEED for HIGH PERFORMANCE and LONG LIFE: the 115/230 volt 60 cycle generator at MAXIMUM POWER SPEED."

This new Winco series also features the exclusive MAXI-WATT Power Control which gives MAXIMUM POWER for unusually heavy motor loads, MAXIMUM EFFICIENCY for normal loads. Tests prove that this 12,000 watt BALANCED Power Winco Engine Generator will carry such loads as a 5 H.P. motor, plus 6000 watts of simultaneous resistive load. The BALANCED Power series is available in a wide selection of models to meet individual electrical requirements. For full details write or call **Wincharger Corporation, East 7th & Division Streets, Sioux City, Iowa.**

AUTOMATIC SWEEP DRIVE

A new sweep drive which automatically sweeps oscillators and other tunable devices through their frequency ranges is now available from Hewlett-Packard Company.

The new unit, Model AC-97C, is a particularly useful motor accessory for Hewlett-Packard's Model 302A wave analyzer. In this application, it sweeps through the entire range of the wave analyzer for automatic plots of harmonics, spurious responses or intermodulation products with an X-Y recorder. It also converts the Model 302A to a sweep oscillator-tuned voltmeter for automatic frequency response measurements, even in noisy systems.

Model AC-97C has two sweep speeds and a neutral. The fast sweep covers the frequency spectrum rapidly while the slow sweep gives a high resolution plot. In neutral position you can tune the driven unit manually. Sweeps can be reversed automatically when limits are reached, thereby providing a continuous sweep for oscilloscope presentations, or, for convenience in X-Y recordings, the sweep can be stopped automatically when the limit is reached.

Sweep speeds can be changed without stopping the drive. Stops are quickly and easily set for any sweep range from 5 degrees revolution of the output shaft to 50 revolutions. Model AC-97A furnishes an output voltage proportional to shaft position for driving the X-axis of a recorder or oscilloscope.

The new sweep drive may be mounted directly on the front panel of the Model 302A wave analyzer or on a bench stand.

The Model AC-97C sweep drive is priced at $275. **Hewlett-Packard Company, 1501 Page Mill Road, Palo Alto, California.**

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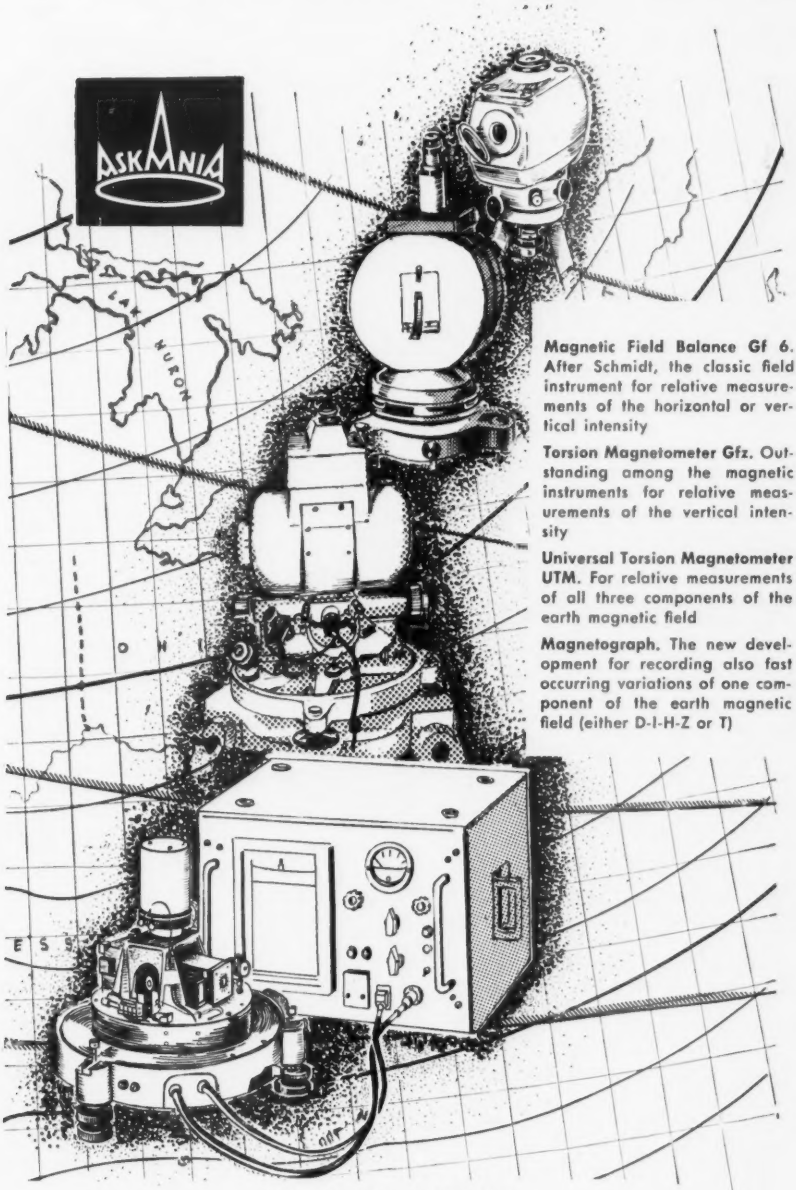
for precise determination of magnetic anomalies



Magnetic Field Balance Gf 6. After Schmidt, the classic field instrument for relative measurements of the horizontal or vertical intensity

Torsion Magnetometer Gfz. Outstanding among the magnetic instruments for relative measurements of the vertical intensity

Universal Torsion Magnetometer UTM. For relative measurements of all three components of the earth magnetic field

Magnetograph. The new development for recording also fast occurring variations of one component of the earth magnetic field (either D-I-H-Z or T)

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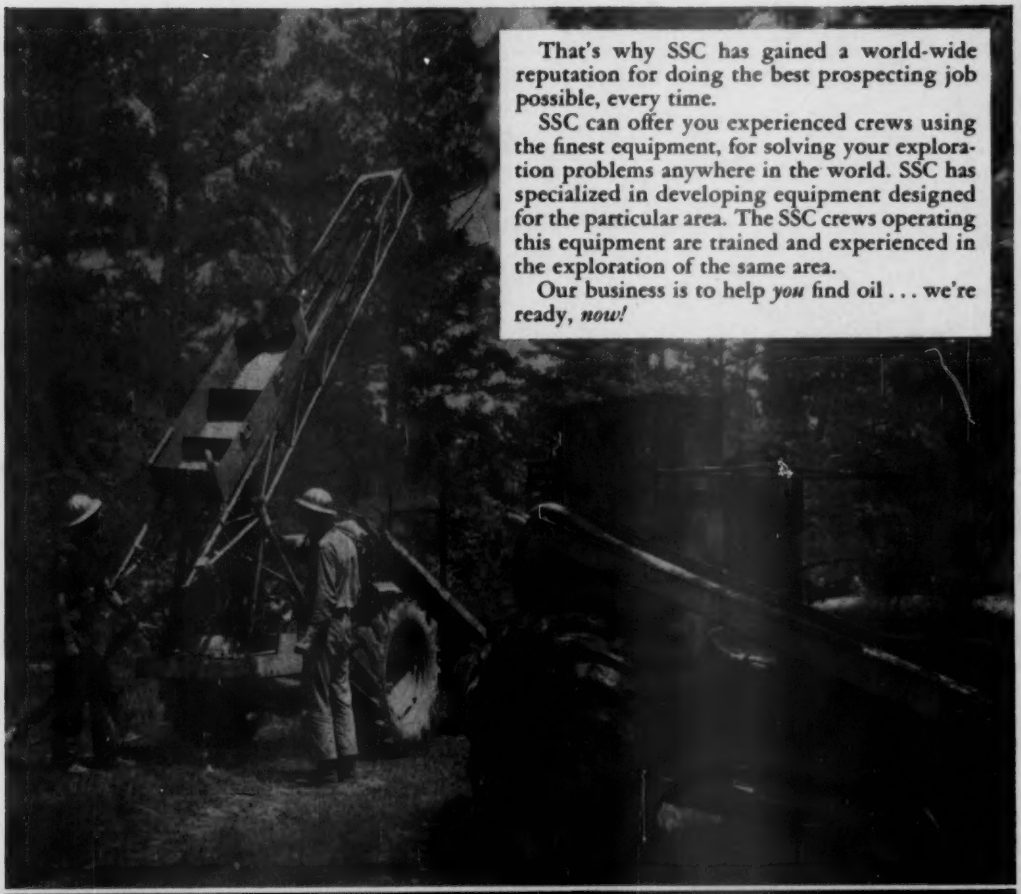

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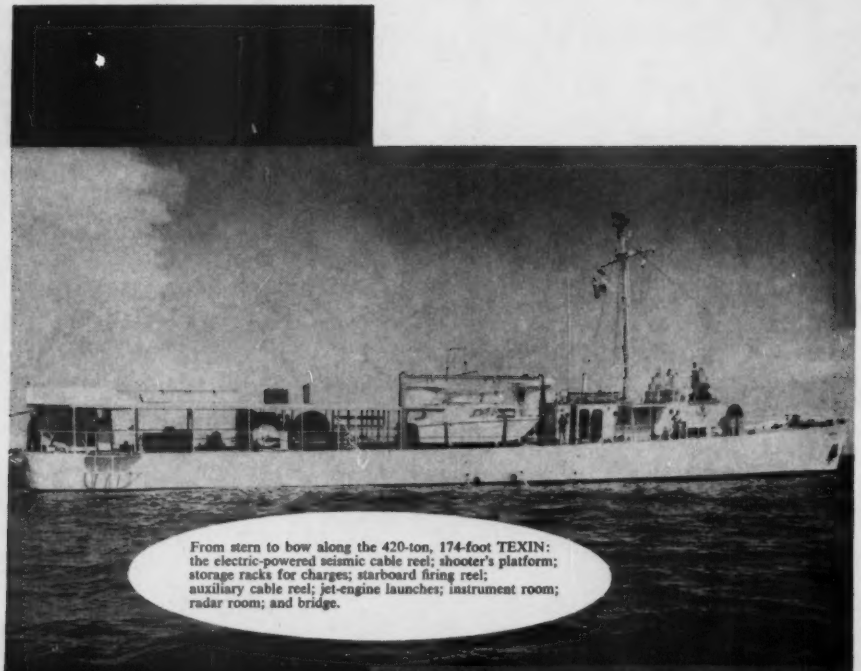

From stern to bow along the 420-ton, 174-foot TEXIN: the electric-powered seismic cable reel; shooter's platform; storage racks for charges; starboard firing reel; auxiliary cable reel; jet-engine launches; instrument room; radar room; and bridge.

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Remote coastal areas . . . far distant from supply ports . . . are the scene of many seismic surveys. These areas are best worked with the single-ship method of exploration. GSI's *new* TEXIN, similar to her sister ship the SONIC, travels to your prospect under her own power, arriving equipped and provisioned for an extensive offshore program. Auxiliary, jet-engine launches project data-gathering facilities into water no deeper than 18 inches . . . giving you a complete marine survey . . . from deep water to shoreline.

Write now for Bulletin S 60-1, describing both the TEXIN and SONIC.

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